NASA/CR—2006-214451 TR06027

Identification of Technologies for Provision of Future Aeronautical Communications

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EXECUTIVE SUMMARY

Background and Introduction

In preparing for near-term spectrum planning activities (e.g., the World Radio Conference 2007 (WRC-07)) as well as longer term aeronautical concepts and transformation (e.g., Next Generation Air Transportation System (NGATS)), aeronautical communications spectrum allocations and roadmaps have been developed and continue to be updated. The roadmap elements reflect current planning for aeronautical communications. Within each aeronautical spectrum band, a common theme is the visibility of limitations of current systems as projected into the 2020 timeframe. These limitations are a driver of the exploration of additional systems and technologies to incorporate into aeronautical spectrum to maintain the ability to meet user demands, increase service provider efficiency, and implement future air transportation system concepts of operation.

The Federal Aviation Administration (FAA) and EUROCONTROL have embarked on a cooperative research and development program in part to address an International Civil Aviation Organization (ICAO) recommendation from the 11th Air Navigation Conference to investigate future technology alternatives and in part to deal with frequency congestion and consequent spectrum depletion in both Core Europe and dense United States airspace. The terms of this research and development program, referred to as Action Plan 17, are outlined in the Terms of Reference document for the program, which has been entitled the "Future Communications Study (FCS)."

NASA's role in Action Plan 17 is to lead the technology investigation efforts. It is the goal of the technology investigation to identify communications technologies that can support the long-term aeronautical mobile communication operating concept. These efforts have been planned as a sequence of studies, including the technology pre-screening (completed in December 2004), technology screening (this study, completed July 2006), and detailed technology investigation (scheduled for completion in May 2007).

The primary result of the technology pre-screening was that there was no one solution that best met all of the needs of aviation stakeholders. Rather, a set of recommended areas of investigation were identified that would support future communications options including:

- More efficient utilization of the very high frequency (VHF) spectrum
- Development of a data link solution in the Distance Measuring Equipment (DME) Band (also referred to as L-Band)
- Use of commercial satellite systems with Aeronautical Mobile Satellite (Route) Service (AMS(R)S) allocations
- Development of a data link solution in the Microwave Landing System (MLS) Extended Band (also referred to as C-Band), primarily for the Terminal Management Area and Airport Surface applications

The pre-screening technology investigations did identify several technologies as being applicable to aeronautical flight critical communications. These included technologies applicable for provision of communications over en route, terminal, and surface airspace domains; technologies that were applicable over oceanic airspace; and technologies that were applicable to airport surface applications.

The primary recommendations for technologies applicable for provision of communications over en route, terminal, and surface airspace domains included:

- VHF Digital Link Mode 3 (VDL 3), shifted to L-Band and given a new abbreviation L-Band data link (LDL)
- P34 in L-Band
- Broadband-VHF (B-VHF), but not as an overlay concept in the VHF Band, but rather shifted to L-Band.

A secondary recommendation was made for Wideband Code Division Multiple Access (W-CDMA) in L-Band.

The pre-screening study results were presented to FAA and EUROCONTROL senior management, ICAO, industry, and the Air Traffic Management Advisory Committee (ATMAC). There was significant feedback on some of the study recommendations, principally in the area of L-Band infrastructure. It was clear, especially in the United States, that L-Band was to be considered an "option of last resort," primarily because of the perceived cost ramifications of additional ground infrastructure and either additional hull-penetrations or costly equipment integration on aircraft.

The FAA intends to comply with the ATMAC recommendations—voice will be kept in the VHF Band for the foreseeable future, using the technology of today (analog 25 kHz DSB-AM) until such time as spectrum pressures require reducing channel spacing to 8.33 kHz. This time will also support learning periods for the use of existing technologies, such as VDL Mode 2, to meet emerging data-link needs. However, the FAA also intends to plan for the future. Should the capacity of the aeronautical VHF spectrum ever prove insufficient to provide the total data-link capacity required, then a new system should be ready and available to ensure that the communications needs of aviation are accommodated.

A second significant set of comments on the pre-screening was received by the ICAO ACP (Aeronautical Communications Panel) at the working group of the whole meeting in June of 2005. Feedback to the study team on the final evaluation process and criteria from the ICAO ACP indicated that the original terms of the FCS were too broad. Rather than specifying a technology that would meet all of the Air Traffic Management (ATM) communications requirements (including voice and data), it was recommended that the technology investigation should focus on a data-only solution, keeping in mind that a future system would augment existing systems, not immediately replace them. Further, the ACP indicated that the genesis of the original evaluation criteria were unclear. The panel asked that a set of evaluation criteria that were directly traceable to the Concept of Operations and Communications Requirements (COCR) document be developed for the Future Radio System (FRS), and that the pre-screening process be repeated.

Objectives and Approach

This report documents the technology screening and recommendations of the Technology Investigation Task (Task 3.2 of AP17) in response to the feedback noted above. As such it identifies and recommends a set of communications technologies that meet future aeronautical communication requirements and are candidates for additional detailed technology assessment. This report also documents a derived set of evaluation criteria traceable to the COCR, a recommended process for detailed technology evaluation and a detailed evaluation of a subset of technologies brought forward from the screening process. The remaining detailed technology evaluations will be completed in the final study phase of FCS technology evaluation (concluding in May 2007).

To perform the technology assessment, a variation of a standard decision support process used in major decision-making software applications and supporting a multicriteria, customer-focused evaluation strategy was defined. This adaptation of the Analytical Hierarchy Process (AHP) to support the FCS technology assessment is shown in figure ES–1.

The first three steps in this process are grouped into a larger category called technology screening. These tasks include the identification of a technology inventory, definition of a threshold or screening filter and screening of technologies. Together these tasks support the identification of the most promising candidates (or a technology "short-list") for the FRS. The second major grouping of process steps includes steps 4 to 9 and comprises the detailed evaluation of technologies. These steps include a more detailed comparison of technologies against a wider set of evaluation criteria, incorporating stakeholder feedback to weight criteria as decision factors supporting a technology decision and scoring technologies.

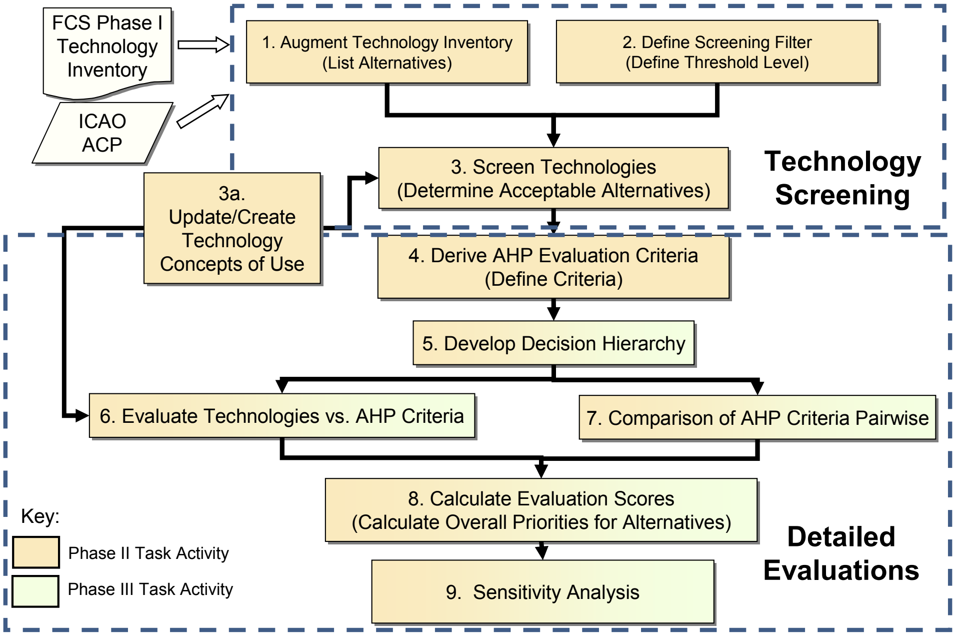


Figure ES–1.—FCS Technology Investigation Methodology.

While all tasks associated with technology screening have been conducted and finalized in this phase of the FCS, only an initial iteration of the tasks associated with detailed evaluations has been performed. A second and final iteration of the detailed evaluations is planned for the final component of the FCS technology investigation task (2006 to 2007).

Results and Conclusions

To conduct the technology screening, an inventory of over 45 technologies was considered. This inventory is shown in table ES–1.

TABLE ES–1.—TECHNOLOGIES INVESTIGATED (TECHNOLOGY SCREENING AND DETAILED EVALUATION)

Technology Family	Candidates
Cellular Telephony Derivatives	W-CDMA (US)/UMTS FDD (Europe), TD-CDMA (US)/UMTS TDD (Europe), CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Wireless Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20
Public Safety and Specialized Mobile Radio	APCO P25, TETRA Release 1, TETRAPOL, IDRA, iDEN, EDACS, APCO P34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS)
Satellite and Other Over Horizon Communication	SDLS, Connexion by Boeing, Swift Broadband (Aero B-GAN), Iridium, GlobalStar, Thuraya, Integrated Global Surveillance and Guidance System (IGSAGS), HF Data Link, Digital Audio Broadcast, Custom Satellite System
Custom Narrowband VHF Solutions	VDL Mode 2, VDL Mode 3, VDL Mode E, VDL Mode 4, E-TDMA
Custom Broadband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA) (at L-Band), LDL, L-Band E-TDMA
Military	Link 16, SINCGARS, HAVEQUICK
Other	APC Telephony

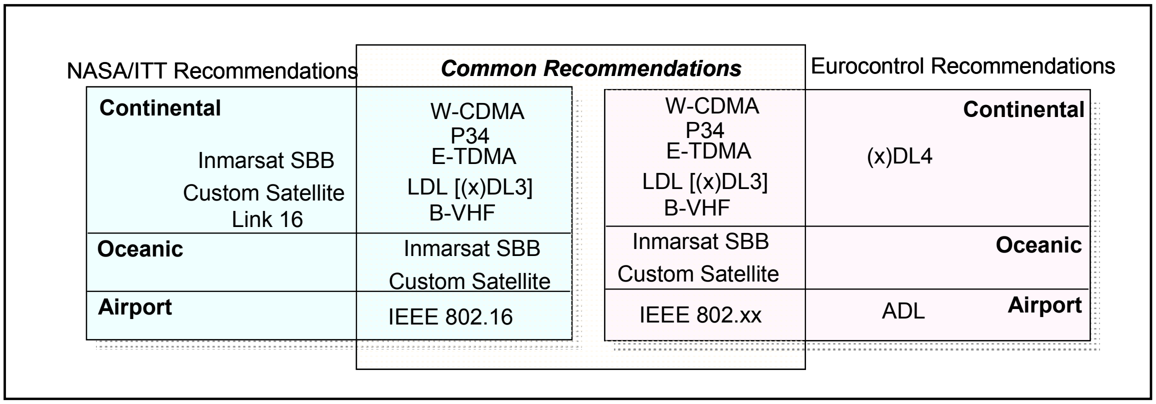


Figure ES–2.—Current Technology Screening Results and a Comparison to EUROCONTROL Technology Short-List.

To identify those technologies most applicable to the needs of aviation, a screening filter was applied, which included the ability to use protected spectrum; the data loading capability; and the technology communication range, where specific threshold values for loading and range are traceable to the requirements of the COCR.

The first component of the filter removed from further consideration those technologies that inherently rely on unprotected spectrum (in other words, not in Aeronautical Mobile (Route) Spectrum (AM(R)S) or Aeronautical Mobile Satellite (Route) Spectrum (AMS(R)S)). These technologies are not viable candidates for the FRS.

The next components of the filter were applied to identify those technologies that meet, exceed, or come close to meeting COCR-derived data capacity and range requirements. To support the application of this filter, technology concept of use definitions, which customize the technology definition to the aeronautical environment, were used.

As a result of the technology screening process eight technologies have been identified as candidates for a general aeronautical communication solution for the FRS (the general solution is also called a continental solution as it applies to all continental flight domains including airport, terminal, and en route). In addition, some additional technologies have been identified as best performers in the context of specific flight domains with unique environments and may warrant separate technology consideration (i.e., oceanic and airport domains). A list of these technologies brought forward from the technology screening process is captured in figure ES–2 (left-hand side). This figure also provides a comparison of the recommended technologies with those technologies brought forward from a parallel screening process conducted by EUROCONTROL. Note that there is a large common set of recommended technologies in the technology "short-list."

The next steps in the AHP address detailed evaluation of technologies. The first step of detailed evaluations is the Derivation of Evaluation criteria. Addressing stakeholder feedback received on the technology pre-screening activities, a structured analysis of the COCR, was undertaken. This structured analysis, along with consideration of ICAO recommendations for future communication systems captured in consensus documentation, was used to derive technical and institutional criteria. In this classification, technical criteria address the required performance and functions of a FRS while institutional criteria address the elements of a technology that make it a viable solution (e.g., cost).

A total of 21 technical technology evaluation criteria and 9 institutional technology evaluation criteria were defined. A summary of the criteria and traceability to source documents is provided in table ES–2.

TABLE ES–2.—SUMMARY OF TECHNOLOGY EVALUATION CRITERIA

	Evaluation Criterion	Description (and Sub-Items such as Capacity (C) and Performance (P))		Traceability
1	Meets ATS Data Link Needs	**A. A/G & G/A Addressed** – Airport, TMA, En Route, Oceanic/Remote, Polar, Autonomous Zone	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency	1. Functions traced to COCR Operational Services (see in table C–5 traceability matrix for verification of needed and complete attributes); 2. Capacity metrics trace to COCR Section 6 3. Need for Priority Levels traces to COCR Section 5 4. Latency metrics trace to COCR Section 5
		B. G/A Broadcast – Airport, TMA, En Route, Oceanic/Remote, Polar, Autonomous Zone	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency	
		C. A/A Addressed – Airport, TMA, En Route/Autonomous, Oceanic/Remote, Polar	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency	
2	Meets AOC Data Link Needs	**A. AOC Data –** Airport**,** TMA, En Route/Autonomous, Oceanic/Remote/Polar	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency	1. Functions traced to COCR Operational Services (see traceability matrix in table C–5 for verification of needed and complete attributes); 2. Capacity metrics trace to COCR Section 6 3. Need for Priority Levels traces to COCR Section 5 4. Latency metrics trace to COCR Section 5
3	Technical Readiness Level	Provides an indication of the technical maturity of the proposed technology		11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 2
4	Standardization Status	Indicates the relevance and maturity of a proposed technology’s standardization status.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 3
5	Certifiability	Provides a relative measure of the candidate’s complexity.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 3
6	Ground Infrastructure Cost	Estimates cost to service provider to provide coverage to a geographically large sector.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 4
7	Cost to Aircraft	Estimates relative cost to upgrade avionics with new technology.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 4
8	Spectrum Protection	Gauges the likelihood of obtaining the proper allocation of the target spectrum.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)

	Evaluation Criterion	Description (and Sub-Items such as Capacity (C) and Performance (P))	Traceability
9	Security – A&I	Assesses whether authentication and data integrity are provided	COCR Security Requirements (table 4–11) Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)
10	Security – Robustness to Jamming	Assesses technology resistance to jamming.	COCR Security Requirements (table 4–11)
11	Transition	Assesses acceptable transition characteristics, including: • Return on partial investment • Ease of technical migration (spectral, physical) • Ease of operational migration (air and ground users)	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-7)

This report also documents the translation of the criteria noted above into evaluation decision factors. The definition and weighting of the decision factors along with the scoring of technologies in this report are presented as interim results in this stage of the FCS. They represent the initial implementation and streamlined execution of the AHP steps 5 to 9 supporting proof-of-concept of the AHP methodology. The results, therefore, can be considered only preliminary at this time. A second and full iteration of the complete detailed evaluation process (steps 5 to 9) will be performed as part of the third and final technology study component of the FCS.

Although mainly preliminary, the initial implementation of AHP steps 5 to 9 led to insightful observations. For example, the Link 16 technology scored poorly when scored against the evaluation criteria and subsequently the evaluation decision factors. Specifically, this technology was determined to be a poor performer of the screened technologies because of cost of the ground and aircraft installation; required operating mode to meet COCR requirements (and corresponding capacity and user limitations); and immature standardization status. Because Link 16's poor performance is a consequence of caparison of the technology's capability to derived evaluation criteria metrics, its evaluation results are not expected to change significantly during final technology evaluations in the third phase of the FCS.

Detailed technology evaluations of satellite communication systems (with a focus on provision of required availability) indicated that Inmarsat Swift Broadband (SBB) would not meet availability requirements. Also, custom satellite solution designed to meet COCR availability requirements would, in fact, require a highly redundant and costly architecture. For these reasons, the satellite solutions are not considered viable solutions for the continental domain. This does not preclude their effective role in providing communication capability in remote and oceanic airspace.

Also supporting refinement of technology evaluation results, detailed analysis of the L-Band propagation environment and P34 and LDL performance in a derived representative L-Band air-ground model provided valuable insight into the performance of these technologies. Specifically, it was found that the L-Band channel model can be considered quite severe in some instances. Considering a mountainous terrain, a mean root-mean-square-delay spread (RMS-DS) was calculated to be on the order of 1.4 μs. In terms of a technology such as P34 (an Orthogonal Frequency Division Multiplexing (OFDM) system with per carrier symbol rate of 4.8 kbps), this channel can be considered a flat fading channel. For a technology such as LDL (with a more simplistic modulation scheme, binary continuous phase frequency shift keying (CPFSK), and with data rate of 62.5 kbps), the channel can be much more severe and considered to be a borderline frequency-selective fading channel (which can result in irreducible bit error rates (BERs) and require more costly mitigation techniques such as adaptive equalization).

Detailed analysis of P34 and LDL also considered the interference potential of these technologies on existing radio-navigation technologies currently operating in the L-Band. The work indicated that the performance of LDL is slightly better than that of P34 in that P34 acts more of an interference source than LDL to both Mode S and Universal Access Transceiver (UAT) receivers. Modeling results indicate that a Carrier-to-Interference (C/I) ratio of 12 to 15 dB is required for minimum degradation of the UAT receiver and 15 dB or better is required to not substantially degrade the Mode S preamble detection behavior, although Mode S interference measurements are recommended to fully understand the interference potential. The results of the P34 and LDL detailed analysis indicate these technologies are still both viable candidates; however, further exploration of the channel model and receiver implementations is warranted for validating LDL performance in this environment, and interference measurement for these technologies against Mode S (and other existing L-Band systems not suitable for analytical interference analysis) are recommended.

One additional detailed analysis performed with regard to L-Band technologies (in general, rather than specific to one technology) was the evaluation of economic feasibility. This analysis was responsive to feedback received on the initial technology pre-screening results that indicated that due to cost constraints, an L-Band solution is only considered should VHF spectrum prove insufficient to provide total required data-link capability. The L-Band business case analysis, provided in section E.1.8, provides a first-order-of-magnitude estimate of required investment for an L-Band aeronautical ground infrastructure.

A final detailed analysis examined the performance of Institute of Electrical and Electronics Engineers (IEEE) 802.16e in the anticipated propagation environment for the C-Band aeronautical channel. Using a channel model adapted from a detailed model developed by Ohio University, the performance of 802.16e was found to be quite good for most of the movement area (incorporating equalization techniques). While this technology has good potential applicability for this domain, additional analysis to look at additional technology features to enhance performance (e.g., Hybrid Automatic Repeat Request (HARQ), fast feedback channel and diversity sub-carrier permutations) is warranted.

In summary, screened technologies with the highest potential applicability to the future communication infrastructure include W-CDMA, P34, LDL, B-VHF (at L-Band), and L-Band E-TDMA as general continental airspace solutions; Inmarsat SBB and a custom satellite solution for remote/oceanic airspace, and 802.16e for the airport domain. Of these technologies, W-CDMA, B-VHF (at L-Band), and L-Band E-TDMA have not undergone detailed analysis. It is recommended that these be candidates for further analysis in the final component of the FCS technology evaluation (2006 to 2007). Additionally, this final phase of the technology evaluation should implement fully steps 5 to 9 of the AHP, evaluating technologies against evaluation criteria and subsequent evaluation decision factors; gathering stakeholder feedback on the relative importance of evaluation decision factors to weight the factors; scoring technologies based on technology evaluations and weighted decision factors; and finally, concluding with specific technology recommendations.

CONTENTS

1. BACKGROUND AND INTRODUCTION

1.1 Spectrum Roadmap for Aeronautical Communications

In preparing for near-term frequency spectrum planning activities (e.g., the World Radio Conference 2007 (WRC-07)), as well as longer term aeronautical concepts and transformation (e.g., Next Generation Air Transportation System (NGATS)), aeronautical communications spectrum allocations and roadmaps have been developed and continue to be updated. The roadmaps can be considered a reflection of air transportation stakeholder inputs on future communication infrastructure. Service providers are operating in an environment where there is great sensitivity to infrastructure costs. This sensitivity is balanced against the desire to implement key elements of the next generation vision to accommodate air traffic growth and to continuously improve transportation system efficiencies. Users also are greatly sensitive to cost and risk. Organizations such as Air Traffic Management Advisory Committee (ATMAC) have outlined the following recommendations for the future communication system:

- Sustain voice communications in the very high frequency (VHF) Band as long as possible
  - Make optimum use of current equipage
  - 8.33 kilohertz (kHz) channel spacing is the preferred first alternative only when current 25 kHz spectrum no longer meets operational needs
- New technical solutions should be pursued only after all nonequipment solutions have been exhausted, including
  - Spectrum allocation
  - Policies and procedures
- Aeronautical Data Link System (ADLS) is important
  - Use existing VHF capabilities/equipment to provide ADLS until Future Communications Study (FCS) decisions and milestones are set
    - VHF Data Link (VDL) Mode 2, 1090 MHz, Universal Access Transceiver (978 MHz)
- Commit to a data-link technology, schedule, and funding by 2007
  - Implement by 2015

With consideration given to stakeholder inputs, the Federal Aviation Administration (FAA) has drafted a United States and European communication roadmap that describes planned implementation of aeronautical communications systems from now through the year 2030. This roadmap comprises four elements, one for each major spectral band with aeronautical allocations. The three primary roadmap elements include

- VHF Band Roadmap
- L-Band Roadmap
- Commercial and Satellite Communications Roadmap

The VHF Band Roadmap, provided in figure 1–1, includes sustainment of current 25 kHz double side band amplitude modulation (DSB-AM) voice communications into the foreseeable future. Where implemented, for example, in Core Europe, 8.33 kHz DSB-AM is maintained for the foreseeable future, with introduction in the United States en route airspace only if needed. The VHF roadmap also includes introduction of initial A/G data communication capability using VHF Digital Link Mode 2 (VDL2) technology beginning in the 2012 timeframe. Finally, the combination of existing analog voice technology in concert with an initial VDL2 data-link capability is shown to enable the possible introduction of a new technology that provides a digital airborne data network with the potential to provide networked voice in the far term. An additional component of the VHF roadmap is the regional deployment of VDL Mode 4 outside of Core Europe.

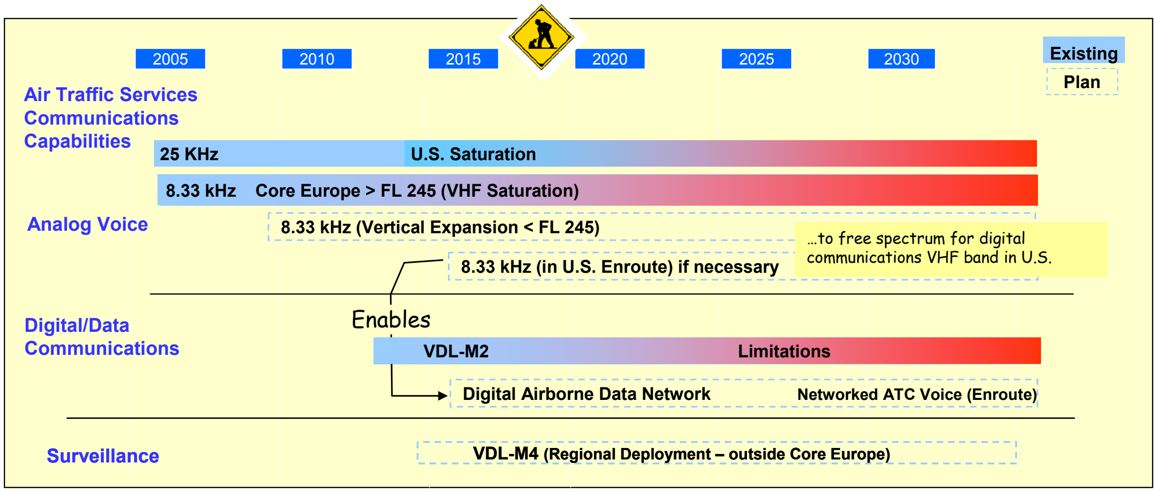


Figure 1–1.—VHF Band Roadmap (Work in Progress).

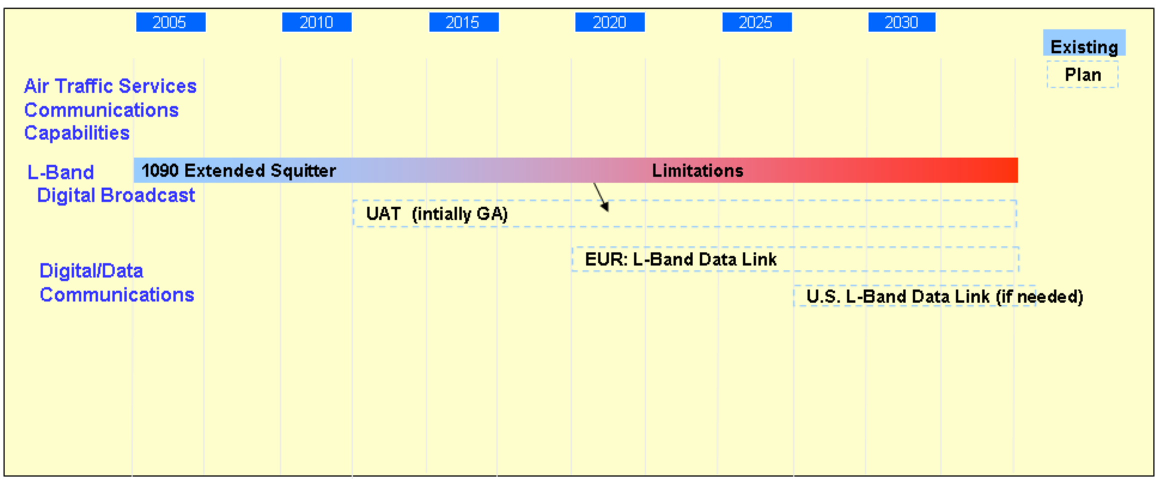


Figure 1–2.—L-Band Roadmap (Work in Progress).

A second roadmap element is the L-Band (also referred to as Distance Measuring Equipment (DME) Band) evolution plan, shown in figure 1–2. Here continuation of Mode S Extended Squitter and introduction of the Universal Access Transceiver (UAT) technologies are captured for Automatic Dependent Surveillance Broadcast (ADS-B) and similar applications. The figure also illustrates the introduction of an L-Band aeronautical data link in Europe in the 2020 timeframe, with introduction in the United States later, only if needed to address capacity and congestion.

The next component of the roadmap is the evolution in the use of commercial and satellite communication technologies, captured in figure 1–3. This roadmap element illustrates the maintenance of oceanic data-link capabilities throughout the planning period. Also in this band, new capabilities to support Aeronautical Operational Control (AOC) and passenger applications as well as System Wide Information Management (SWIM) applications are introduced between 2010 and 2015. In the far term, 2020 and beyond, there is consideration given to the use of satellite technologies for safety services in the en route airspace.

The final component of the aeronautical roadmap addresses aeronautical C-Band spectrum (also referred to as the Microwave Landing System (MLS) extended band). To date, a separate roadmap graphic for this band has not been published with other roadmap elements. The current and planned use of this band is for microwave landing systems; however, localized safety-related data-link implementations (e.g., in the vicinity of an airport) are also under consideration.

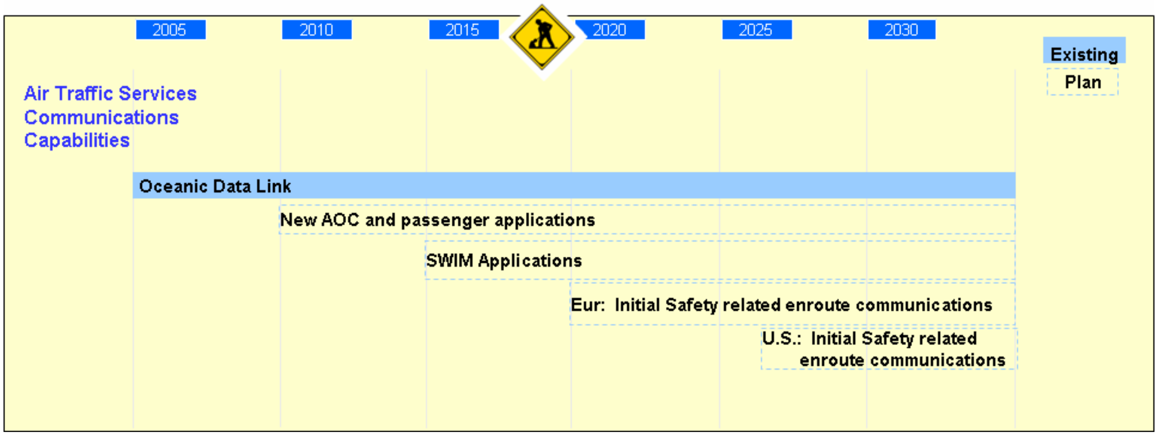


Figure 1–3.—Commercial and Satellite Technology Roadmap (Work in Progress).

These communication roadmap elements reflect current planning for aeronautical communications. Within each band, a common theme is the visibility of limitations in current systems as projected into the 2020 timeframe. These limitations are a driver for the exploration of additional systems and technologies for incorporation into aeronautical spectrum to maintain the ability to meet user demands, increase service-provider efficiency and implement future air transportation system concepts of operation. In continued coordination with European states, the International Civil Aviation Organization (ICAO), the U.S. Joint Planning Development Office (JPDO), and with user stakeholders, the roadmaps will be monitored and refined as appropriate.

1.2 Global Aeronautical Communications Objectives and AP-17

The genesis of current aeronautical communication objectives can be traced to the ICAO Eleventh Air Navigation Conference (ANC-11), held in Montreal from 22 September through 3 October 2003. One of the highlights of this formal ICAO conference was the official report of the Technical and Operational Matters in Air Traffic Control Committee (Committee B). This report noted the current state of aviation communications and made several recommendations to advance this state. The observations included:

- The aeronautical mobile communication infrastructure has to evolve in order to accommodate new functions
- This evolution would likely require the definition and implementation of new terrestrial and/or satellite systems that operate outside the VHF Band
- A variety of (somewhat divergent) views had been presented with regard to the future evolution of aeronautical mobile communications
- The universally recognized benefits of harmonization and global interoperability of air ground communications should not be forgotten when pursuing optimization of local solutions
- The successful gradual introduction of data communications should be continued to complement and replace voice for routine communications

Based on these observations, several conference recommendations were made:

- Develop an evolutionary approach for global interoperability of air-ground communications
- Conduct an investigation of future technology alternatives for air-ground communications
- Prove compliance with certain minimum criteria before undertaking future standardization of aeronautical communication systems

The FAA and EUROCONTROL have embarked on a cooperative research and development program in part to address these ICAO recommendations and in part to deal with frequency congestion and consequent spectrum depletion in both Core Europe and dense United States airspace. The terms of this research and development program are outlined in the Terms of Reference document for the program, which has been entitled the "Future Communications Study (FCS)." By agreement, joint FAA and EUROCONTROL research and development activities require terms of reference, which are referred to as "action plans" and are numbered sequentially. The terms of reference for the FCS are detailed in Action Plan 17, and the U.S. National Aeronautics and Space Agency (NASA), the FAA, and EUROCONTROL all have defined roles in the research and development activities.

NASA's role in Action Plan 17 is to lead the technology investigation efforts. It is the goal of the technology investigation to identify communications technologies that can support the long-term mobile communication operating concept. These efforts have been performed as a sequence of studies including the technology pre-screening (completed in December of 2004), technology screening (this study, completed July 2006), and detailed technology investigation (scheduled for completion in May 2007).

1.3 FCS 2004 Pre-Screening results

The work plan for Action Plan 17 identified the initial task of the technology investigation as a technology pre-screening. This pre-screening would "provide the high-level capabilities, projected maturity for the timeframe for usage in aviation, and their potential applicability to aviation." The technology investigation activities that were completed as part of the pre-screening included:

- Development of an inventory of potentially applicable technologies
- Development of an evaluation methodology, evaluation criteria, and evaluation metrics
- Development of recommendations for the use of aviation spectrum
- Performance of a technology pre-screening

In order to identify all technologies that may be applicable to aeronautical communications, a multi-faceted approach was used for technology identification. This included two released Requests for Information from NASA to solicit technology candidate inputs from industry; EUROCONTROL inputs received from European manufacturers; and identification of candidate technologies by ICAO Aeronautical Communication Panel (ACP) Working Group-C (WG-C) member states.

To complement these three sources, an independent survey of widely used and successful commercial and military technologies was conducted by the contracting team. The intent of this survey was to identify technologies that offered potential value to air/ground (A/G) communications that might not have been suggested through the NASA-, EUROCONTROL-, and ICAO-generated technology suggestions. In general, those latter suggestions are characterized by the notion of a technology "stakeholder" or advocate. The remainder technologies that were identified in the survey process are somewhat disadvantaged in that they lack a stakeholder or advocate. Ultimately, to assure standardization and adoption of a technology, a significant advocacy will be required by multiple aviation stakeholders. Nevertheless, it was deemed important to the goals of the study to "leave no stone unturned." In all, over 50 technologies were identified and evaluated.

A "Concept of Use" description was developed for the evaluated technologies and was the basis for evaluation of the candidate technologies in accordance with the chosen evaluation criteria. The chosen evaluation criteria and metrics used in the pre-screening were the culmination of a process of collaboration and peer review among the technology assessment groups (NASA and ITT for FAA; and QinetiQ for EUROCONTROL), a requirements identification group, and an FAA panel of experts. A high-level overview of the evaluation criteria used in the pre-screening is shown in table 1–1.

TABLE 1–1.—PRE-SCREENING EVALUATION CATEGORIES AND CRITERIA

Category	Evaluation Category Description	Item #	Criteria
Communications Capabilities	Communication capabilities needed to support current and emerging ICAO ATM concepts	1	Meets Voice Needs
		2	Meets Basic Datalink Needs
		3	Meets Expanded Datalink Needs
Maturity for Aeronautical Environment	Technical maturity as well as the recognition of the safety assurance required for aeronautical standardization and certification	4	Technology Readiness Level
		5	Standardization
		6	Certification
Cost	Cost of infrastructure used by the service provider as well as the cost of avionics equipage by aircraft	7	A/G Communications Infrastructure
		8	Avionics
Other	Availability of suitable AM(R)S spectrum, support for security, and practical accommodation of transition	10	Spectrum Protection
		11	Security
		12	Transition

The pre-screening work was completed in December 2004. Recommendations of this phase were briefed to FAA and EUROCONTROL management, as well as to ICAO and industry. The primary result of the 2004 pre-screening study was that there was no one solution that best meets all of the needs of aviation stakeholders. Rather, it was noted that there are issues that aviation should investigate; and future communications investigations should consider:

- More efficient utilization of the VHF spectrum
- Development of a data-link solution in the DME Band (also referred to as L-Band)
- Use of commercial satellite systems with AMS(R)S allocations
- Development of a data-link solution in the MLS Extended Band (also referred to as C-Band), primarily for the Terminal Management Area (TMA) and Airport Surface applications

The pre-screening technology investigations did identify several technologies as being applicable to aeronautical flight critical communications. These included technologies applicable for provision of communications over en route, terminal, and surface airspace domains (collectively referred to as the continental domains); technologies that were applicable over oceanic airspace; and technologies that were applicable to airport surface applications.

The primary recommendations for technologies applicable for provision of communications over en route, terminal, and surface airspace domains included:

- VHF Digital Link Mode 3 (VDL 3), shifted to L-Band and given a new abbreviation, L-Band Data Link (LDL)
- P34 in DME Band
- Broadband-VHF (B-VHF) (but not as an overlap concept in the VHF Band, but rather shifted to L-Band)

A secondary recommendation was made for Wideband Code Division Multiple Access (W-CDMA) in the DME Band (secondary because there were substantial questions regarding infrastructure cost and ability to meet push-to-talk (PTT) connection requirements with the technology).

Technologies applicable for provision of communications over specific airspace domains included Inmarsat Aero-BGAN (Swift Broadband (SBB)) and Iridium in the oceanic domain; and 802.16e (using MLS Band spectrum) for airport surface applications.

The pre-screening study results were presented to FAA and EUROCONTROL senior management, ICAO, industry, and the ATMAC. There was significant feedback on some of the study recommendations, principally in the area of L-Band infrastructure. It was clear, especially in the United States, that L-Band was to be considered an "option of last resort," primarily because of the perceived cost ramifications of additional ground infrastructure and either additional hull-penetrations or costly equipment integration on aircraft.

Additional stakeholder recommendations, specifically the ATMAC recommendations identified in section 1.1 above, were received and considered. These recommendations were incorporated into the notional FAA data-link roadmap, and have influenced the current direction of the study. It is clear that the FAA intends to comply with the ATMAC recommendations—voice will be kept in the VHF Band for the foreseeable future, using the technology of today (analog 25 kHz DSB-AM) until such time as spectrum pressures require reducing channel spacing to 8.33 kHz. This time will also support learning periods for the use of existing technologies to meet emerging data-link needs. However, the FAA also intends to plan for the future. Should the capacity of the aeronautical VHF spectrum ever prove insufficient to provide the total data-link capacity required, then a new system should be ready and available to ensure that the communications needs of aviation are accommodated.

This is completely in line with the ICAO ANC 11 observation that (highlighting added) "This evolution would likely require the definition and implementation of new terrestrial and/or satellite systems that operate outside the VHF band." Subsequent FCS technology investigation focus has been made to support the understanding of issues associated with hosting a communications system in either L-Band or C-Band and with the potential use of satellites for flight critical communications. Final study outputs should be a set of recommendations that can be taken to RTCA to start standardization of this future system.

A second significant set of comments on the pre-screening was received by the ICAO ACP at the working group of the whole meeting in June of 2005. Feedback to the study team on the final evaluation process and criteria from the ICAO ACP indicated that the original scope of the FCS was too broad. Rather than specifying a technology that would meet all of the Air Traffic Management (ATM) communications requirements (including voice and data), it was recommended that the technology investigation focus on a data-only solution, keeping in mind that a future system would augment existing systems, not immediately replace them. Furthermore, the ACP indicated that the genesis of the original evaluation criteria was unclear. The panel asked that a set of evaluation criteria directly traceable to the Concept of Operations and Communications Requirements (COCR) document be developed for the FRS, and that the pre-screening process be repeated. These observations and requests led to a revised set of objectives for the second phase of the FCS technology assessment, the technology screening. These revised objectives are addressed in this study.

1.4 Purpose of This Report

This report documents the technology assessment and recommendations of the Technology Investigation Task (Task 3.2) of AP17. As such it identifies and recommends a set of communications technologies that meet future aeronautical communication requirements based on the technology screening process and that should be brought forward for additional detailed technology assessment.

This report also documents a recommended process for detailed technology evaluation, a derived set of evaluation criteria traceable to the COCR, and the initial detailed evaluation of the technologies brought forward from the screening process. The detailed technology evaluation will be completed in the final study phase of FCS technology evaluation (concluding in May 2007).

2. TECHNOLOGY ASSESSMENT APPROACH

2.1 Approach Introduction and Overview

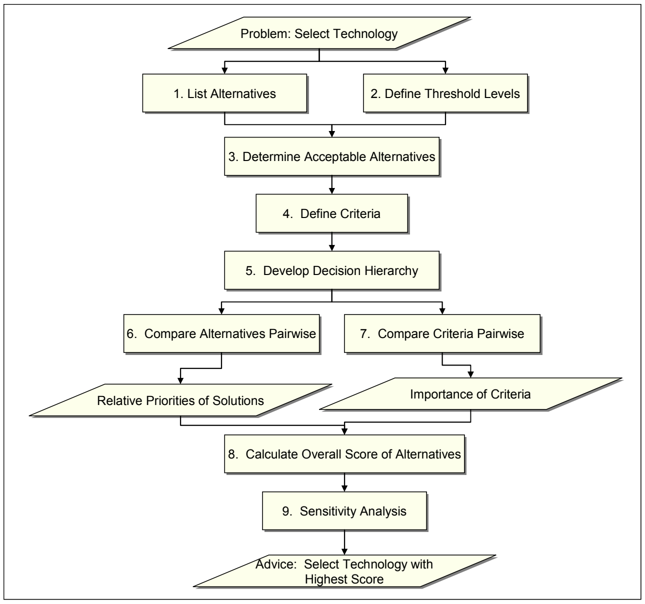
For many reasons, decision making in the aeronautical environment can be considered complex. There are a large number of stakeholders with differing needs and desires. There are many and sometimes conflicting factors that influence stakeholder technology decisions with regard to the aeronautical environment. And, specific to the FRSs, there are many alternative technologies to consider. In a desire to be responsive to stakeholder feedback received on the initial technology pre-screening effort as well as to identify a technology assessment approach that can accommodate a complex decision-making environment, a range of decision-making methodologies were investigated. Methodologies of particular interest were those that are integral parts of business process improvement strategies, such as Six Sigma.

One identified methodology thought to be particularly applicable to the Future Radio System (FRS) technology investigation task is the Analytical Hierarchy Process (AHP). This methodology is process-oriented, accommodates multi-criteria decisions, and employs customer-focused strategies. It is also utilized in major decision-making software applications, such as Expert Choice. Like all decision-making methodologies, the AHP, or AHP, has both strengths and weaknesses. It can accommodate many aspects of a decision organized into a decision hierarchy; group decision making can be supported; a clear and comprehensive structure is applied to the decision-making process; and it provides a means of assessing relative importance of decision factors.

With these benefits come some limitations. Specifically, there is an implied assumption that identified decision factors are independent, which is not always the case. Additionally, the calculations supporting the process are complex and often require custom software. Finally, the process can be time intensive to implement. In spite of these drawbacks, the AHP was found to have great applicability to the technology investigation task. Its comprehensive structure and direct incorporation of customer inputs provide a means to foster stakeholder buy-in during the evaluation process, rather than after the process is complete.

The standardized AHP is composed of nine task steps. The organization of these steps and a brief description of each phase are provided in figure 2–1.

The process shown above has been adapted for application to the evaluation of technologies for the FRS. Specifically, in step 6, the standard AHP suggests a relative comparison of technology solutions with respect to each evaluation criteria. This comparison results in the identification of the relatively best technology solutions, but it does not identify if any solution can meet the criteria and hence, in the current application, the needs of aviation. An alternative approach is to perform an absolute evaluation of technologies against criteria, and in the process evaluate which technologies meet most or all of the evaluation criteria. This alternative step identifies the best relative solution as well as determines which solutions meet future communication system requirements.



	Name	Description
1	List Alternatives	First step in AHP; identify and list all alternatives
2	Define Threshold Levels	Define minimum requirements that an alternative has to fulfill
3	Determine Acceptable Alternatives	Review all alternatives with respect to threshold levels; alternatives that do not meet these requirements are dismissed
4	Define Criteria	Criteria used to judge the alternatives are defined; several techniques are possible (e.g. pro/con analysis, critical success factor technique, etc)
5	Develop Decision Hierarchy	A hierarchy that identifies the decision goal, and provides an organization of analysis criteria
6	Comparison of Alternatives Pairwise	For each criterion, stakeholders evaluate all candidate solution alternatives pairwise (every possible combination of alternatives is judged with respect to each criterion); this results in a relative ranking of each alternative
7	Comparison of Criteria Pairwise	Stakeholders perform a pairwise comparison of all evaluation criteria; this results in the relative importance of each criterion
8	Calculate Overall Priorities for Alternatives	A linear additive function is used to calculate the overall ranking of an alternative (the relative rankings of an alternative are multiplied by the importance of the corresponding criteria and summed over all criteria)
9	Sensitivity Analysis	"What-if" analysis is used to identify the sensitivity of results to changes in rankings of alternatives and criteria

Figure 2–1.—Overview of Standard Analytical Hierarchy Process.

A second more minor change in the current adaptation of the AHP is the addition of a supplemental step that specifically addresses the creation of a technology concept of use which supports technology screening and detailed evaluation. The resulting methodology for technology evaluation in this study is shown in figure 2–2.

Similar to the standard AHP, the methodology defined for technology evaluation consists of nine steps. The first three, which include identification of a technology inventory, definition of a screening or threshold filter, and the screening of technologies have been grouped into a larger category called technology screening. These tasks together support the identification of the most promising candidates from the technology inventory for the FRS. They apply a specific set of threshold filters that correspond to key requirements of the FRS supporting the identification of a technology "short-list" for further evaluation. The second major grouping of process steps includes steps 4 to 9 and comprises the detailed evaluation of technologies. These steps include a more detailed comparison of technologies to a wider set of evaluation criteria; incorporating stakeholder feedback to weight criteria as decision factors supporting a technology decision; and calculating technology evaluation scores.

All tasks associated with technology screening have been conducted and finalized in this phase of the FCS. Further, an initial iteration of the tasks associated with the detailed evaluations has been performed. The comprehensive application of the technology evaluation process defined in figure 2–2 requires detailed evaluation of technologies brought forward from the technology screening and a substantial set of stakeholder inputs supporting step 7 to determine the relative importance of decision factors used for calculating technology scores. As a result of recommendations made in the 2004 technology pre-screening task, a detailed investigation of the majority of the technologies resulting from the technology screening has been performed. Investigation of remaining technologies is planned for the final component of the FCS technology investigation task (2006 to 2007). Additionally, a preliminary set of stakeholder feedback was solicited during this study to support the application and evaluation of the AHP (step 7).

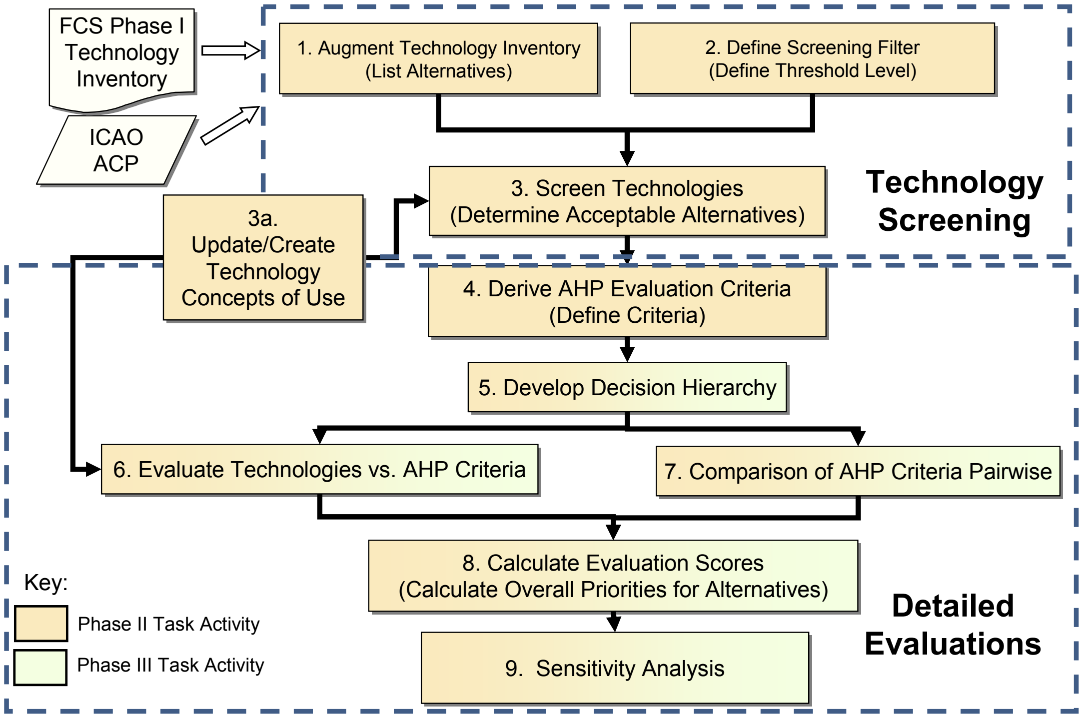


Figure 2–2.—FCS Technology Evaluation Methodology.

This data was used to develop a preliminary set of technology scores. A focused solicitation of stakeholder feedback and second iteration of steps 6 to 9 is planned for the final component of the FCS technology investigation task (2006 to 2007).

Additional information specific to the methodology applied to perform each step in the technology evaluation AHP is provided in the following subsections.

2.2 Technology Screening Activities

There are three primary steps in the AHP supporting technology screening. These steps, and a fourth supporting activity, include:

- Step 1: Augment Technology Inventory
- Step 2: Define Screening Filter
- Step 3: Screen Technologies
- Step 3a: Update/Create Technology Concept of Use

As described in section 1.3 in the initial pre-screening technology evaluation study (2004), a multi-faceted approach was used to identify candidate technologies for evaluation. This approach included:

- Two NASA-released Requests for Information soliciting technology candidate inputs from industry
- Inputs to EUROCONTROL received from European manufacturers
- Identification by the ICAO Aeronautical Communications Panel (ACP) Working Group-C (WG-C) of several technologies of especial interest to member states, or thought to be potentially applicable
- An independent survey of widely used and successful commercial and military technologies

During the pre-screening activities, over 50 technology candidates were identified. Due to the comprehensive approach applied in 2004, the focus of step 1 in the technology screening was the *augmentation* of the candidate technology list to accommodate new technologies specifically suggested through ICAO ACP WG-C. These technologies were identified in ACP meetings, review of ACP WG-C meeting reports, and review of technology definition technical papers.

The process applied to perform step 2, Define Screening Filter, was to identify a clear and traceable (to COCR requirements) screening threshold to support the identification of applicable FRS technology candidates within technology families.

Upon selection of the filter, Step 3 would then consist of applying the filter to the technologies and identifying those technologies that should be brought forward from the technology screening for further consideration. Supporting the application of the screening filter is the task to define/update technology concepts of use. A concept of use can be defined as a mapping of a technology into a system; specific to this task, it provides the basic description of how the required COCR services would be provisioned by a technology implementation. This understanding of how the technology could be applied and implemented as a future aeronautical communication system is needed to support the assessment of how the technology performs against the defined screening filters.

To create the concept of use material for the technologies, several steps were performed. These included:

1. Review of a list of available services and architecture configurations for a technology and identification of the service(s)/architecture most appropriate for aeronautical communications
2. Review of modes of operation for a technology and identification of the most applicable for this application
3. Definition of the set of physical architecture parameters supporting the implementation of the identified services and operational modes (e.g., modulation, coding, data rate, and range)
4. Creation of a description of the integration of the candidate's architecture for aeronautical communications into the existing aeronautical infrastructure

Many of the required technology concepts of use were created during the FCS pre-screening task in 2004. These concepts were reviewed and updated as necessary for the current study. As needed, new technology concepts of use were created for new technologies added to the technology inventory.

Upon completion of the technology screening, the results obtained were compared to analogous screening activities performed by EUROCONTROL. A comparison of the results is presented in this report.

2.3 Detailed Technology Evaluation Activities

There are six steps in the AHP supporting detailed technology evaluation. They include:

- Step 4: Derive AHP Evaluation Criteria
- Step 5: Develop Decision Hierarchy
- Step 6: Evaluate Technologies Versus AHP Criteria
- Step 7: Comparison of AHP Criteria Pairwise
- Step 8: Calculate Evaluation Scores
- Step 9: Sensitivity Analysis

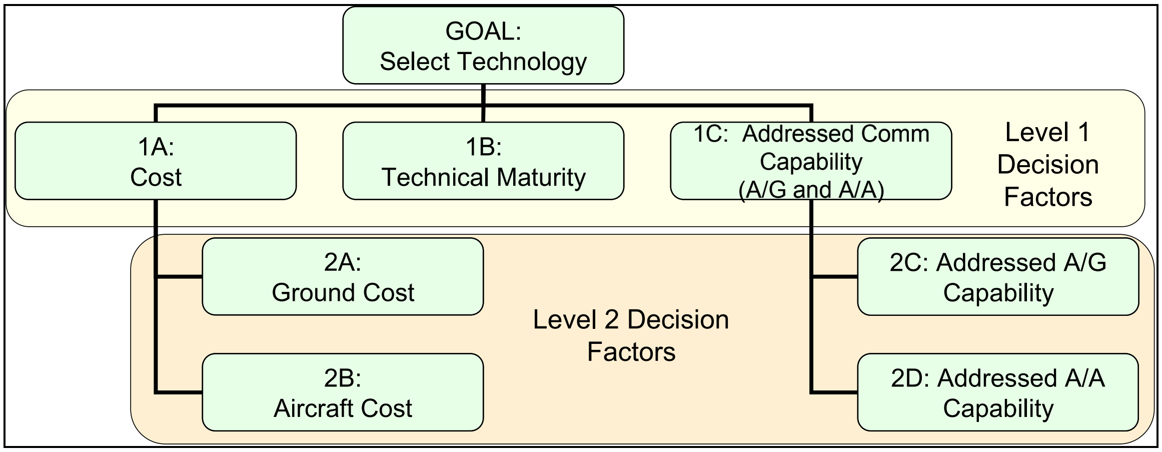


Figure 2–3.—Sample Decision Hierarchy.

As a starting point in deriving AHP evaluation criteria, the criteria applied to the 2004 pre-screening task activity were reviewed. It was recognized that two major classifications of evaluation criteria, technical and institutional, were used in the prior task. Technical criteria address the required performance and functions of the FRS, while institutional criteria address the strategic objectives of the future communication system or the elements of a technology that make it a viable solution. Both categories of criteria have significance to the selection of technology and this categorization was maintained in the present study.

To derive technical criteria, a rigorous analysis of the COCR was performed. This included a functional analysis of the concepts of operations for the FRS (as defined in the COCR) to identify required functional capabilities, and identification of applicable performance specifications from the COCR. This approach was in response to feedback received on 2004 pre-screening technology evaluation activities that requested documented traceability of evaluation criteria to requirements. Because institutional criteria address strategic elements of a communication implementation such as cost and risk, which are not explicitly identified in the COCR, a different approach was required for deriving institutional criteria. Specifically, ICAO consensus documents were reviewed to identify strategic elements to be considered in future aeronautical implementations. These elements were translated into evaluation criteria.

After identification of evaluation criteria, the next step (step 5) in the AHP is the development of a decision hierarchy. There are many approaches to defining this hierarchy, but the end result has a common structure. At the highest level of the hierarchy, the structure identifies the analysis goal. For this study, the goal is to identify a technology for the FRS. The first branch of the hierarchy includes the Level 1 or global decision factors. Lower levels of the hierarchy include a decomposition of decision factors into component factors. A sample decision hierarchy structure is provided in figure 2–3. The structure includes a defined goal and two representative layers of a decision hierarchy.

In figure 2–3, the Level 1 or global decision factors are decomposed (as applicable) into lower level decision factors. This structure supports a later step in the AHP to determine relative importance of decision factors. By organizing the decision factors in a hierarchical fashion, evaluation criteria can be addressed in manageable groups (one branch at a time) to assess relative importance, and the results can be rolled up into higher levels of the hierarchy.

For the FRS technology evaluation decision hierarchy, the starting point for building the hierarchy is the evaluation criteria. A simple, but ineffective structure would be inclusion of each criterion as a global decision factor. To achieve the gains of implementing a hierarchical structure, technical and institutional criteria were reviewed to determine a meaningful organization mindful of the benefits of organizing criteria into smaller subsets of a hierarchy balanced with the understanding that adding multiple levels can increase the complexity of later AHP analysis. For example, in subsequent step 7 of the AHP, the relative importance of decision factors is assessed within each branch of the hierarchy via pair-wise comparisons.

As there are (N * (N-1))/2 pair-wise comparisons of N factors, care is required to define a hierarchy that adds structure but not unwarranted complexity to the organization of decision factors.

Two steps follow the definition of the decision hierarchy. The first is the evaluation of technologies against the defined decision factors (step 6 in the AHP). To perform this step, technologies are initially evaluated against the evaluation criteria derived from the COCR (technical criteria) and the ICAO consensus documents (institutional criteria). To perform the technical criteria assessment, the defined technology concept of use for each technology is used to identify applicable flight domains, applicable functionality (yes/no capability determination for each functional technical criterion), provisioned data rate, maximum number of users supported, ability to provision quality of service (QoS), and ability to meet latency requirements of the COCR. This information extracted from the concept of use is then compared to COCR requirements. For each technical criterion, a "meets/doesn't meet" decision is made for the technology. A representative set of technology information and comparison to COCR requirements is provided in figure 2–4.

Note in figure 2–4 that performance requirements of the COCR used for comparison to the technology information are those associated with "COCR Phase 2" operations. The COCR describes a two-phased implementation of future operating services and concepts, COCR Phases 1 and 2. Based on the aeronautical communication roadmap (see section 1.1), a need for a new technology

Technology Family	**Cellular**
Flight Domain	
APT	Yes
TMA	Yes
ENR	Yes
OR	No
P	No
AOA	Yes
Functionality	
A/G & G/A Addressed	Yes
Ground Originated Broadcast	Yes
A/A Addressed	No
Air Originated Broadcast	No
Data Rate (kbps)	
Data Rate for ATS (kbps)	500
Data Rate for ATS+AOC (kbps)	500
Max Number Users	300
Max Number of Users (SATCOM architectures)	N/A
QoS	Yes
Latency	Yes
	N/A

PHASE 2		**Airport SV**		**TMA SV AEXEC**		**ER SV AEXEC**			**OR SV AEXEC**	
		HD	**LD**	**HD**	**LD**	**HD EU**	**HD US**	**LD**	**HD**	**LD**
Separate ATS	**UL**	12.8	7.1	22.0	22.2	20.9	22.4	21.0	19.8	19.6
	DL	11.3	5.2	10.3	10.7	9.8	13.5	10.5	8.5	8.3
	UL&DL	19.6	7.3	24.5	25.1	23.5	27.0	24.0	20.3	19.9
Separate AOC	**UL**	113.0	14.1	0.3	0.2	52.4	96.1	64.1	24.0	18.2
	DL	6.7	1.2	2.4	2.2	1.4	2.7	1.8	0.6	0.4
	UL&DL	131.2	14.1	2.6	2.3	58.6	106.9	72.6	24.4	18.2
Combined ATS&AOC	**UL**	120.0	24.6	22.0	22.2	119.1	168.3	134.8	82.1	62.8
	DL	13.4	5.4	11.1	11.8	10.2	13.[illegible]	10.9	8.6	8.3
	UL&DL	144.3	24.8	25.2	25.8	119.4	168.9	135.2	82.2	62.9

Table 6-20: Air/Ground Capacity Requirements (kbps) – Phase 2

Figure 2–4.—Comparing Technology Information to Performance Criteria Values From the COCR.

supporting data-link communications is identified to apply to the mid- to far-term communication vision, corresponding, at least in part, to the COCR Phase 2 operating concept of the COCR. As a result, the requirements used for assessing technologies were those that correspond to the COCR Phase 2 operations.

To perform an assessment of technologies for institutional evaluation criteria, each institutional criterion is defined a value associated with a red/yellow/green rating system. The metrics used to evaluate the criteria are the same as those defined for the 2004 pre-screening technology assessment. For example, the metric associated with the institutional criterion called "standardization status" are shown in figure 2–5. A complete set of metrics for institutional criterion can be found in section 2.2 of the 2004 pre-screening report[1] and in appendix D.

After assessment of technologies for each technical and institutional criterion, an assessment of technology performance for each defined Level-1 or global decision factor (from the decision hierarchy) is made. Note that the decision hierarchy may combine or rollup a set of evaluation criteria into a global decision factor. To assess a meets/doesn't meet value for each decision factor accounting for technical performance, if a technology meets the requirements of each evaluation criterion that comprises the decision factor, the technology is deemed to "meet" the decision factor. If one or more of the component evaluation criteria are not satisfied by the technology, then the technology is judged to "not meet" the decision factor. For decision factors that encompass institutional criterion, if a red rating is associated with any component criterion for a particular technology, the technology is evaluated as "not meeting" the decision factor; otherwise (i.e., if all component institutional criterion ratings are yellow and/or green), the technology is considered to "meet" the decision factor. An example of technology evaluation against decision factors is shown in figure 2–6.

Standardization Status
[G, Y, or R status is assigned based upon the existence of applicable standards for the candidate] **Assessed as:** Green: candidates that have a publicly available aeronautical standard; Yellow: candidates are supported by a mature commercial standard Red: candidates for which a supporting standard does not exist or is not publicly available

Figure 2–5.—Example Metrics for Institutional Criterion (Metrics for Standardization Status).

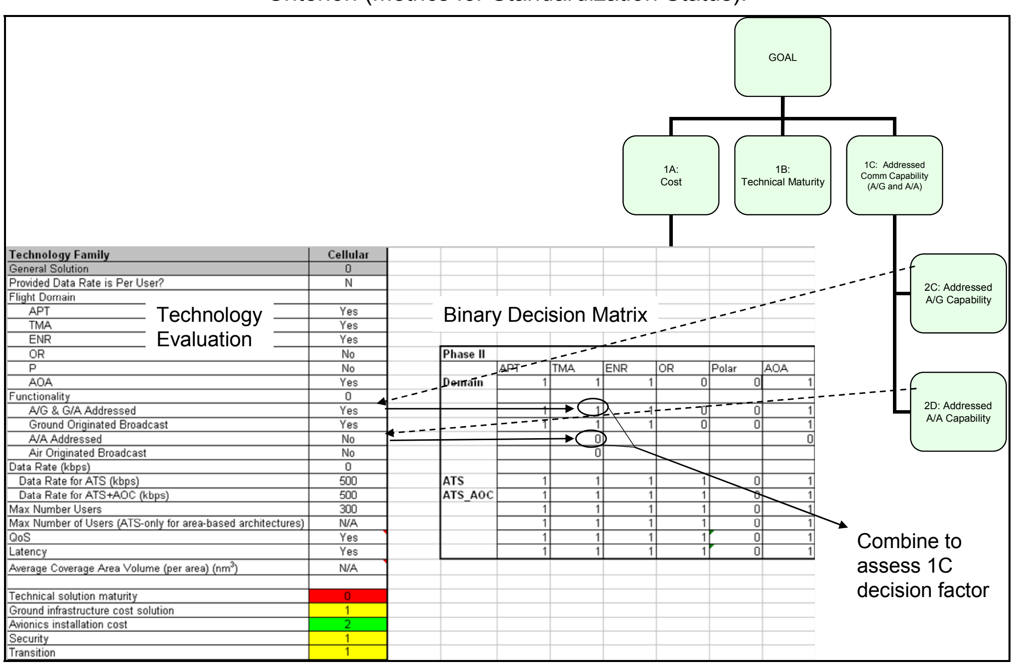


Figure 2–6.—Example—Evaluating Technologies Against Decision Factors.

Note in figure 2–6 that Decision Factor 1C "Addressed Comm Capability" includes two component evaluation criteria, namely "Addressed A/G Capability" and "Addressed A/A Capability." A technology is first rated each component criterion individually. For the example shown above, the representative technology meets the first criterion (i.e., it can provide an addressed A/G communication capability) but does not meet the second criterion (i.e., it cannot provide an A/A address communication capability). A binary matrix is used to record the results of this individual evaluation criterion assessment (1 = meets requirement; 0 = doesn't meet requirement). Then, to determine if the representative technology meets Decision Factor 1C (Addressed Comm Capability), which is a combination of the two component evaluation criterion, the binary scores of the individual evaluation criterion are combined (i.e., multiplied). In the example above, the score of the addressed A/G capability assessment (1) is multiplied by the addressed A/A capability assessment (0) to arrive at a result of 0 for assessing if the technology meets the Addressed Comm Capability (decision factor 1C). In other words, since A/A addressed functionality is not met and this is a component of decision factor 1C, the technology is judged as not meeting this decision factor.

A second step in the AHP performed after the definition of the decision hierarchy is the comparison of AHP criteria pair-wise (AHP step 7). This is a key step for incorporating stakeholder feedback into the AHP. While the decision factors used to assess technologies are derived from evaluation criteria traceable to the requirements of the COCR and ICAO consensus documentation, the weighting of these factors is made using direct input from stakeholders. Specifically, all decision factors are compared pair-wise through a survey of stakeholders. Stakeholders are asked, "Is decision factor X extremely/very strongly/strongly/moderately or equally more/less important to decision factor Y?" for all combinations of decision factors. For this study, as an initial iteration of AHP step 7, a preliminary population of a single stakeholder group was surveyed. An excerpt of the survey is shown in figure 2–7.

Results of the pair-wise survey of decision factors are used to populate a pair-wise comparison matrix. In this matrix, numerical scores are applied to survey results. Specific values include:

- Extremely more important than: 9
- Very strongly more important than: 7
- Strongly more important than: 5
- Moderately more important than: 3
- Equally important to: 1
- Moderately less important than: 1/3
- Strongly less important than: 1/5
- Very strongly less important than: 1/7
- Extremely less important than: 1/9

An example application of these values to a pair-wise comparison of survey results is shown in figure 2–8. Note that in figure 2–8, the decision factors in the column can be considered "decision factor X" and those in the row across the top can be considered "decision factor Y" when applying the statement "decision factor X is extremely/very strongly/strongly/moderately or equally more/less important to decision factor Y."

The comparison matrix can be generated to reflect a single stakeholder survey response, or averaged for a set of stakeholders or across stakeholder sets. To calculate averaged results, the geometric mean of each individual comparison score is computed.

Pair-Wise Comparison of CTQ Metrics

ID	CTQ Metric A		Relative Magnitude	Relationship Sense	CTQ Metric B
1	Meets ATS_G-A-Broadcast_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
2	Meets ATS_A-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
3	Meets ATS&AOC_G-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
4	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
5	Meets ATS&AOC_A-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements

Figure 2–7.—Excerpts of Stakeholder Survey Comparing Decision Factors Pair-Wise.

Scale:

1 - equally important	1/3 - moderately less important
3 - moderate more important	1/5 - strongly less important
5 - strongly more important	1/7 - very strongly less important
7 - very strongly more important	1/9 - extremely less important
9 - extremely more important	

Is [row] more important than [column]? (>1)	Meets ATS_G-A-Addressed_COCR Requirements	Meets ATS_G-A-Broadcast_COCR Requirements	Meets ATS_A-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	Meets ATS&AOC_A-A-Addressed_COCR Requirements	Provides highly mature technical solution	Provides low ground infrastructure cost solution	Provides low avionics installation cost solution	Provides highly secure/safe solution	Provides low-risk/low complexity service provider transition
Meets ATS_G-A-Addressed_COCR Requirements		5	7	1	7	5	3	0.333	3	1	3
Meets ATS_G-A-Broadcast_COCR Requirements	0.2		0.2	0.143	3	0.2	0.2	0.2	0.2	0.143	0.2
Meets ATS_A-A-Addressed_COCR Requirements	0.1429	5		3	5	3	3	3	3	0.2	3
Meets ATS&AOC_G-A-Addressed_COCR Requirements	1	7	0.333		3	5	1	1	1	0.2	1
Meets ATS&AOC_G-A-Broadcast_COCR Requirements	0.1429	0.3333	0.2	0.333		3	3	3	3	0.2	3
Meets ATS&AOC_A-A-Addressed_COCR Requirements	0.2	5	0.333	0.2	0.333		0.333	0.333	0.333	0.2	0.333
Provides highly mature technical solution	0.3333	5	0.333	1	0.333	3		0.333	0.333	0.2	0.333
Provides low ground infrastructure cost solution	3	5	0.333	1	0.333	3	3		3	0.2	0.333
Provides low avionics installation cost solution	0.3333	5	0.333	1	0.333	3	3	0.333		0.2	0.333
Provides highly secure/safe solution	1	7	5	5	5	5	5	5	5		5
Provides low-risk/low complexity service provider transition	0.3333	5	0.333	1	0.333	3	3	3	3	0.2	

Figure 2–8.—AHP Comparison Matrix of Pair-Wise Survey Results.

The final part of AHP step 7 is the calculation of decision factor weights using the pair-wise comparison results. This step requires matrix mathematics including determining the eigenvalues of the matrix, determining the eigenvector corresponding to the largest eigenvalue, and then normalizing the resulting eigenvector. This results in a set of decision factor weights ranging from zero to 1 where the sum of all weights equals 1. A sample set of decision factor weights is shown in table 2–1.

TABLE 2–1.—SAMPLE DECISION FACTOR WEIGHTS

Decision Factor	Weight
Meets ATS_G-A Addressed_COCR Requirements	0.1820
Meets ATS_G-A Broadcast_COCR Requirements	0.0279
Meets ATS_A-A Addressed_COCR Requirements	0.1222
Meets ATS&AOC_G-A Addressed_COCR Requirements	0.0793
Meets ATS&AOC_G-A Broadcast_COCR Requirements	0.0723
Meets ATS&AOC_A-A Addressed_COCR Requirements	0.0285
Provides highly mature technical solution	0.0403
Provides low ground infrastructure cost solution	0.0920
Provides low avionics installation cost solution	0.0480
Provides highly secure/safe solution	0.2327
Provides low-risk/low complexity service provider transition	0.0748

Technology under Evaluation:	0		
Selected Ranking Perspective:	CAA (sample)		
Technology Decision Factor Assessment			
Level 1 Decision Factor	**Meets**	AHP Assessment Value	**SCORE**
Meets ATS_G-A-Addressed_COCR Requirements	☑	18.20%	0.182
Meets ATS_G-A-Broadcast_COCR Requirements	☑	2.79%	0.0279
Meets ATS_A-A-Addressed_COCR Requirements	☐	12.22%	
Meets ATS&AOC_G-A-Addressed_COCR Requirements	☑	7.93%	0.0793
Meets ATS&AOC_G-A-Broadcast_COCR Requirements	☑	7.23%	0.0723
Meets ATS&AOC_A-A-Addressed_COCR Requirements	☐	2.85%	
Provides highly mature technical solution	☐	4.03%	
Provides low ground infrastructure cost solution	☑	9.20%	0.092
Provides low avionics installation cost solution	☑	4.80%	0.048
Provides highly secure/safe solution	☑	23.27%	0.2327
Provides low-risk/low complexity service provider transitior	☑	7.48%	0.0748
	☑	**TOTAL**	**0.809**

Figure 2–9.—Sample Calculation of Technology Score.

The final two steps in the technology evaluation AHP are the calculation of technology evaluation scores and sensitivity analysis. The overall technology scores result from the combination of technology evaluation outputs (from AHP step 6) with the weighted ranking of AHP global decision factors (from AHP step 7). Recall that technology evaluations result in a meets/doesn't meet decision for each decision factor. For each decision factor that is "met" by the technology, the weighted value of the decision factor is added to the total technology score. The resulting technology scores range from 0 to 1. A sample calculation of a technology score is shown in figure 2–9.

In this study, based on a preliminary survey of stakeholders, a preliminary evaluation of technologies was made. The full implementation of the detailed evaluation of technologies will be complete in the final phase of the FCS technology investigation (2006 to 2007).

To perform a sensitivity analysis (AHP step 9), subsets of the decision factors can be isolated and technology scores re-computed. Additionally, scores can be calculated for individual stakeholders, a common stakeholder group, or across stakeholder groups. For the preliminary technology evaluation included in this study, the sensitivity analysis performed was against two subsets of decision factors. In addition to overall technology scores, preliminary technology scores specific to technical decision factors as well as institutional decision factors were also computed. Results of the application of the methodology described above are included in the subsequent sections of this report.

3. TECHNOLOGY SCREENING

This section describes the work performed to identify the set of technologies from the technology inventory that are most applicable to the future needs of aviation as outlined in the COCR. Performing a technology screening supports identification of the most promising technology candidates on which to focus detailed technology evaluations. The technology screening process and results are addressed in the following sections:

- Augment Technology Inventory (AHP Step 1)—Section 3.1
- Defining Screening Filter (AHP Step 2)—Section 3.2
- Screen Technologies—Section 3.2
- Define Technology Concept of Use—Section 3.2.1
- Compare Technologies versus. Screening Metrics (AHP Step 3)—Section 3.2.2
- Recommended Technology Shortlist and Comparison to EURCONTROL Screening–Section 3.2.3

3.1 Augment Technology Inventory

This section describes the technology inventory evaluated for applicability to the FRS. A summary of the technology inventory is provided followed by a brief overview of each technology.

3.1.1 Augment technology inventory (AHP Step 1)

Figure 3-1, the identification of a technology inventory is the first step in the process to evaluate technologies for the FRS.

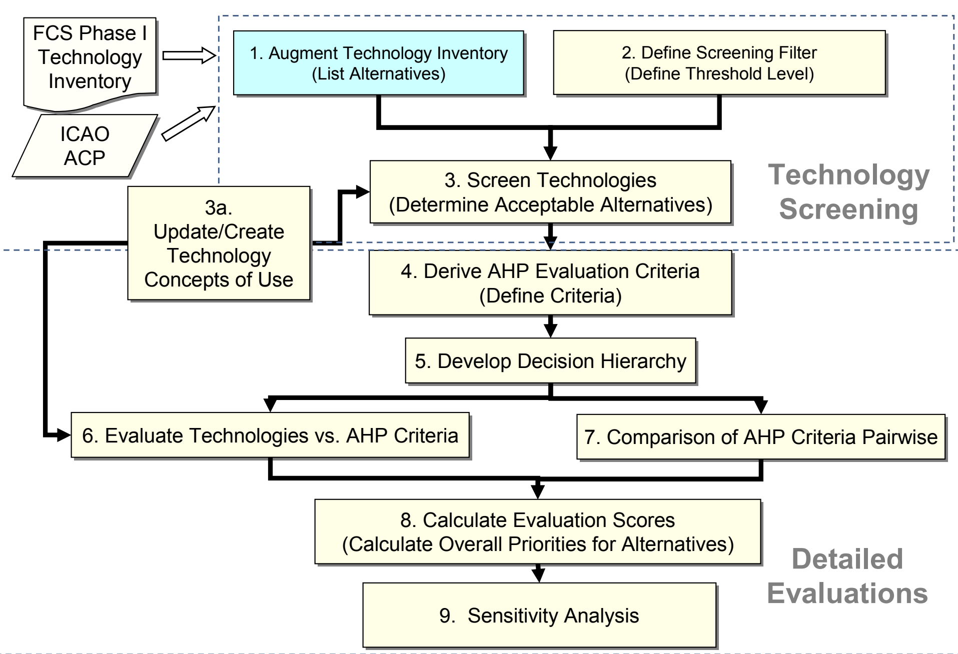


Figure 3–1.—FCS Technology Evaluation AHP—Step 1.

As noted in Section 2.2, the technology inventory defined in the initial technology pre-screening activities of the FCS (2004) was used as a starting point for identifying candidate technologies for evaluation. Through technology surveys and NASA's release of Requests for Information (RFIs), a set of 50 technologies were initially identified for evaluation during the first work segment of the FCS. The identified technologies were grouped into larger technology families, characterized by similarities in user requirements, services offered, and reference and physical architectures. This organization facilitates the evaluation process. The initial set of identified candidate technologies from the 2004 study is listed in table 3–1.

TABLE 3–1.—TECHNOLOGIES INVESTIGATED IN FCS INITIAL TECHNOLOGY PRE-SCREENING (2004)

Technology Family	Candidates
Cellular Telephony Derivatives	TDMA (IS-136), CDMA (IS-95A), CDMAone (IS-95B), CDMA2000 1xRTT, W-CDMA (US)/UMTS FDD (Europe), TD-CDMA (US)/UMTS TDD (Europe), CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Wireless Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20, ETSI HIPERPAN, ETSI HIPERLAN, ETSI HIPERMAN
Public Safety and Specialized Mobile Radio	APCO P25 Phase 1, APCO P25 Phase 2, TETRA Release 1, TETRAPOL, IDRA, iDEN, EDACS, APCO P34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS), Project MESA
Satellite and Other Over Horizon Communication	SDLS, Connexion by Boeing, Inmarsat Swift Broadband (Aero B-GAN), Iridium, GlobalStar, Thuraya, Integrated Global Surveillance and Guidance System (IGSAGS), HF Data Link, Digital Audio Broadcast
Custom Narrowband VHF Solutions	VDL Mode 2, VDL Mode 3, VDL Mode 3 w/SAIC, VDL Mode E, VDL Mode 4, E-TDMA
Custom Broadband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA) (at L-Band)
Military	Link 16, SINCGARS, EPLRS, HAVEQUICK, JTRS
Other	APC Telephony

The inventory defined above was augmented to include three additional technologies that were introduced and described in meetings and working papers, including those presented at ICAO ACP WG-C and other aeronautical communication forums including the NASA Integrated Communication, Navigation, and Surveillance Conference and Workshop. Specifically, these include:

- L-Band Data Link (LDL)[2,3,4]—This candidate is the proposed narrowband VHF Digital Link Mode 3 (VDL-3) technology band-shifted for broadband implementation (with a re-designed physical layer)
- L-Band E-TDMA[5]—This candidate is the proposed narrowband Enhanced-Time Division Multiple Access (E-TDMA) technology band-shifted for broadband implementation (with a re-designed physical layer)
- Custom Satellite System[6]—This candidate is a custom-designed satellite implementation (similar to proposals for Satellite Data Link System (SDLS)) specifically designed for aeronautical communications.

It should be noted that other technology concepts that may have been recently conceptualized or named in aeronautical forums, but for which no technical description yet exists, were not added to the inventory as sufficient information to perform an evaluation does not exist. In addition to the additions noted above, the table of candidate technologies was modified to accommodate the following observations:

- For the cellular technology family, there is a clear evolutionary path from first generation systems to second- and third-generation systems and beyond. Due to the strong evolutionary environment, the first- and second-generation systems are being superseded and the corresponding older technology is slowly becoming obsolete. Therefore, the consideration of older technologies provides no value for aeronautical communications technology analysis, and cellular standards directly replaced by mature standards were not maintained as stand-alone technology candidates. Affected candidates include IS136 (superseded by GSM and CDMA2000), IS-95 A/B (superseded by CDMA2000), and CDMA 2000 1xRTT (superseded by CDMA 2000 1xEV).

- For the 802 wireless technologies, the European Telecommunications Standards Institute (ETSI) and Institute of Electrical and Electronics Engineers (IEEE) standards bodies are working to harmonize the defined standards. In some cases, the ETSI standards are a subset of the IEEE standards definition (e.g., HIPERMAN standard is a subset of 802.16). In other cases, the similarities are such that separate consideration of the standards is not warranted. As a result, HIPERMAN, HIPERPAN, and HIPERLAN are not explicitly defined as candidates; rather, they are considered under the umbrella of 802.16, 802.15, and 802.11, respectively.
- APCO P25 has been defined for two phases of operation (namely, COCR Phases 1 and 2). COCR Phase 1 has mature standards for a digital Frequency Division Multiple Access (FDMA) trunked and conventional radio configuration using 12.5 kHz channels. Development of the COCR Phase 2 standards, for a two-slot Time Division Multiple Access (TDMA) configuration on 12.5 kHz Frequency Division Multiplexing (FDM) channels, is ongoing. At this time, the COCR Phase 2 standards are not publicly available and consideration of this mode as a separate technology candidate not warranted. As such, the P25 technology candidate is only for the COCR Phase 1 definition.
- Project MESA, within the public safety radio standards family, is a concept for ETSI and TIA to collaborate on a mobile broadband specification for public safety. Available documents specific to Project MESA include a Statement of Requirements and System Overview. The System Overview indicates that this specification is a communication architecture, rather than a specific waveform specification.[7] Due to lack of specific technical specifications and its definition as a communication architecture, this concept was not maintained in the technology inventory.
- VDL3 and VDL3 with SAIC are essentially the same technology with VDL3 with SAIC proposed as a means of increasing VDL3 channel capacity through the use of a receiver signal processing enhancement. Separate consideration of this capability as a separate technology is not warranted; thus, only one VDL3 technology candidate was considered.
- Enhanced Position Location Reporting System (EPLRS) is a military technology with essentially the same air-interface and functions as Link 16. While defined for 400 MHz ground tactical operations, its Link 16 counterpart is defined for 1 GHz (more in line with L-Band channel of interest) with available avionics. Due to the technology similarities, better applicability of Link 16 to civil aeronautical application, and more readily available technical information for Link 16, EPLRS was removed from the inventory. It was noted, however, that if Link 16 was found to perform well, that additional consideration should be given to EPLRS.
- Finally, JTRS is defined as a common architecture framework for software radios rather than a specific waveform. As such, it is not truly a technology candidate and was not maintained in the inventory.

Adding the new technologies to the candidate list and accommodating the observations noted above, the resulting candidate set of technologies investigated in this study is shown in table 3–2.

TABLE 3–2.—TECHNOLOGIES INVESTIGATED (TECHNOLOGY SCREENING AND DETAILED EVALUATION)

Technology Family	Candidates
Cellular Telephony Derivatives	W-CDMA (US)/UMTS FDD (Europe), TD-CDMA (US)/UMTS TDD (Europe), CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Wireless Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20
Public Safety and Specialized Mobile Radio	APCO P25, TETRA Release 1, TETRAPOL, IDRA, iDEN, EDACS, APCO P34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS)
Satellite and Other Over	SDLS, Connexion by Boeing, Swift Broadband (Aero B-GAN), Iridium, GlobalStar,

Technology Family	Candidates
Horizon Communication	Thuraya, Integrated Global Surveillance and Guidance System (IGSAGS), HF Data Link, Digital Audio Broadcast, Custom Satellite System
Custom Narrowband VHF Solutions	VDL Mode 2, VDL Mode 3, VDL Mode E, VDL Mode 4, E-TDMA
Custom Broadband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA) (at L-Band), LDL, L-Band E-TDMA
Military	Link 16, SINCGARS, HAVEQUICK
Other	APC Telephony

3.1.2 Technology Overview

The following sections provide a brief introduction to the technologies defined in the technology inventory. This material, in part, summarizes technology descriptive information included in the initial technology pre-screening report.[8]

3.1.2.1 Cellular Telephony Derivative Technologies

The technologies in this family encompass the existing and evolving standards relating to cellular telephony. This family has seen a fast-paced evolution and implementation in the past 20 years characterized in terms of cellular "generations." The first generation or 1G systems appeared in the early 1980s. These systems were followed by 2G, 2.5G, and currently 3G systems, which now offer high data rate services, Internet access, location-based services, and multimedia applications. This evolution is expected to continue with the implementation of 4G systems, which offer high data rates, greater bandwidth efficiency, and advanced antennas and coding. The 4G systems are currently under development.

Seven cellular technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–3. Additional descriptive information on these technologies can be found in section 3.2 of the initial technology pre-screening report.[9]

TABLE 3–3.—OVERVIEW OF CELLULAR TELEPHONY TECHNOLOGIES[10]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	W-CDMA/ UMTS FDD	3G evolution of the European Global System for Mobile Communication (GSM); A direct spread, wideband frequency division duplex CDMA standard developed by GPP	2 Mbps	No explicit limitation	FDD	2 x 5 MHz
2	TD-CDMA)/ UMTS TDD	Time division counterpart to W-CDMA. Uses a combined TDMA and CDMA scheme and designed for hot spots for dual mode handsets that support W-CDMA and TD-CDMA	2 Mbps	30 km	TDD	5 MHz
3	CDMA2000 3x	This technology is a combination of multiple CDMA2000 1xEV components; it is a multi-carrier, frequency duplex CDMA standard	4 Mbps	100 km	FDD	5 MHz
4	CDMA2000 1xEV	This is an evolution of the first CDMA standards (IS-95A/IS-95B); It provides a data only mode (DO) and a data and voice mode (DV); This technology includes synchronous cells utilizing a time phased spreading code on the forward link	2 Mbps	100 km	FDD	2 x 1.25 MHz

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
5	GSM/GPRS/ EDGE	GSM is a frequency division duplex TDMA 2G standard; General Packet Radio Services (GPRS) is an extension to GMS providing higher data rate packet service; Enhanced Data Rates for GMS Evolution (EDGE) is a technology that gives GSM the capacity to handle 3G services for mobile telephony (3x data capacity of GPRS)	400 kbps	35 km	FDD	2 x 200 KHz
6	TD-SCDMA	This is a time division duplex CDMA standard similar to TD-CDMA; it is being developed by the TD-SCDMA Forum for use in China.	2 Mbps	40 km	TDD	1.6 MHz
7	DECT	This is a European TDD standard incorporating TDMA and FDMA for Digital Enhanced Cordless Telecommunications	552 kbps	300 m	TDD	1.728 MHz

3.1.2.2 IEEE 802 Wireless Derivatives Technologies

This technology family encompasses the hierarchy of cellular wireless network standards. They range from small personal area networks (PANs) that correspond to operations within about 30 feet to wide area networks (WANs) that operate over large regions (e.g., one or more cities and extended suburbs). The technologies in this family offer unicast and broadcast/multicast data services. Operations are organized into two basic topologies. The Basic Service Set (BSS) is a set of stations controlled by a single Access Point (AP); and the Independent Basic Service Set (IBSS) is a self-contained network without a dedicated access point, a mesh network with peer-to-peer communications.

Four IEEE 802 wireless technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–4. Additional descriptive information on these technologies can be found in section 3.3 of the initial technology pre-screening report.[11]

TABLE 3–4.—OVERVIEW OF IEEE 802 WIRELESS TECHNOLOGIES[12]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	IEEE 802.11	This is an evolving set of standards for Local Area Networks (LANs). 802.11(b) is a Direct Sequence Spread Spectrum (DSSS) waveform similar to CDMA in cellular telephony. 802.11(a) and (g) use Orthogonal Frequency Division Multiplexing (OFDM), similar to the modulation used for wireline Digital Subscriber Line and for digital TV and radio broadcasts.	Up to 54 Mbps	~ 100 meters	FDD	a/g: 20 MHz; b: 25 MHz
2	IEEE 802.15	This is an evolving set of standards for Personal Area Networks (PANs) that use a variety of modulation and access techniques	Up to 55 Mbps	~ few meters	FDD	~ 20 MHz
3	IEEE 802.16	This is an evolving set of standards for Metropolitan Area Networks (MANs). It uses 256 sub-carrier OFDM and includes an option for 2048 sub-carrier OFDM. A subset of the carriers are used for pilot signals to provide phase reference across the frequency band	Up to 63 Mbps	~ 10 km (> with multiple cells)	FDD, TDD	1.75 – 20 MHz
4	IEEE 802.20	This is an evolving set of standards for	Approx	~ 15 km	FDD	1.25 x N

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
		Wide Area Networks (WANs). It aims to provide better mobility management and wider area coverage as compared to 801.16.	2 Mbps	(> with multiple cells)		MHz for N = 1, 4, 8, 16

3.1.2.3 Public Safety and Specialized Mobile Radio Technologies

Public Safety and Specialized Mobile Radio technologies are standards and systems in use for public safety and service communications. They are a subset of a larger standard family called Land Mobile Radio Systems. There are both open and proprietary technologies within this family. The open standards have been developed in various forums including:

- APCO Standards—standards developed by the TR-8 Private Radio Technical Standards Committee, under sponsorship by TIA
- TETRA Standards—standards produced by Project Terrestrial Trunked Radio (TETRA), a technical body of the ETSI
- TETRAPOL—standards developed publicly by manufacturers of the TETRAPOL Forum and the TETRAPOL Users' Club
- IDRA—standards developed by the Association of Radio Industries and Businesses (ARIB)

Proprietary standards have been developed by radio manufacturers, including Motorola (iDEN™) and Ericsson (EDACS).

Eight Public Safety and Specialized Mobile Radio technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–5. Additional descriptive information on these technologies can be found in section 3.4 of the initial technology pre-screening report.[13]

TABLE 3–5.—OVERVIEW OF PUBLIC SAFETY AND SPECIALIZED MOBILE RADIO TECHNOLOGIES[14]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	APCO P25	A narrowband (12.5 kHz) digital voice and data system that can operate in either a trunked or conventional radio mode. It provides direct mobile to mobile communications as well as full duplex base-station repeater mode.	9.6 kbps	7.6 – 35 km	FDM	12.5 kHz
2	TETRA Release 1	This is a narrowband system (25 kHz) using 4-slot TDMA to provide digital voice and data services to up to four simultaneous users.	36 kbps	3.8 – 17.5 km	FDM	25 kHz
3	TETRAPOL	This standard provides voice and data capability over frequency division multiplexed narrowband channels (10 and 12.5 kHz).	8 kbps	8 – 28 km	FDM	10, 12.5 kHz
4	IDRA	This is a six-slot TDMA voice and data system providing up to 64 kbps data rate in 25 kHz channels. It is an evolution of Japan's first digital dispatch standard (RCR STD-32).	64 kbps	20 – 40 km	FDM	25 kHz
5	iDEN™	This is a proprietary Motorola narrowband TDMA voice and data system that is functionally equivalent to IDRA. The system uses six-slot TDMA.	64 kbps	5 – 40 km	FDM	25 kHz

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
6	EDACS	EDACS is a proprietary system that utilizes a standardized air interface (EIA TSB 69 series). It operates in 25 or 12.5 kHz channels providing 4.8 – 9.6 kbps (using GFSK modulation)	9.6 kbps	Power limited	FDM	12.5, 25 kHz
7	APCO P34	A wideband (50, 100 and 150 kHz channels) digital voice and data system that provides high data rate IP services. It provides direct mobile to mobile communications as well as full duplex base-station repeater mode.	76.8 – 691.2 kbps (SAM)[15]; 88 – 864 kbps (IOTA)[16]	150 – 187.5	FDM	50, 100, 150 kHz
8	TETRA Release 2 (TAPS)	This is a wideband evolution of TETRA that is an adaptation of the Enhanced GPRS standard (cellular General Packet Radio Services operating over EDGE) intended to be a TETRA 1 overlay network	473 kbps	< 5 km	FDM	50, 100, 150 kHz
9	TETRA Release 2 (TEDS)	This is a wideband evolution of TETRA incorporating multi-carrier modulation over a time division multiple access structure intended to be fully compatible with TETRA 1	36 – 691 kbps	< 5 km	FDM	50, 100, 150 kHz

3.1.2.4 Satellite and Other Over Horizon Communication Technologies

Traditionally, satellite systems have provided communication services to remote areas or areas that cannot accommodate a ground infrastructure (e.g., oceanic regions). Currently, there are hundreds of functional satellites providing communication services including broadcast and mobile telephony. Due to similarity in the extent of geographic coverage, nonsatellite over-the-horizon communications were included in this technology family.

Nine satellite and over horizon communication technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–6. Additional descriptive information on these technologies can be found in section 3.5 of the initial technology pre-screening report.[17]

TABLE 3–6.—OVERVIEW OF SATELLITE AND OVER HORIZON TECHNOLOGIES[18]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	Custom Satellite System/SDLS	This candidate addresses custom satellite solutions specifically designed to address the needs of aviation. An example system concept is the Satellite Data Link System (SDLS), a European Space Agency funded effort for a satellite based system for safety services. This concept utilizes bent-pipe geostationary satellites and CDMA at L-band.	As needed (one defined SDLS service provides 6.4 - 30 kbps per user)	N/A	FDD	N/A
2	Connexion by Boeing	This is a high data rate system targeted at APC and AAC communications. Boeing indicates that the extension to ATS and AOC communications seems feasible. Services are offered in Ku-band on geostationary satellites.	Up to 1 Mbps (forward); Up to 5 Mbps (return)	N/A	FDD	N/A

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
3	Inmarsat SBB	Inmarsat was initiated as an intergovernmental agency providing global safety and communication services for the maritime community. In 1999, the organization was transformed into a private company, and focus of the service offerings expanded beyond the maritime community. Basic low data rate aeronautical services are offered while planned high-data rate offerings (e.g. Swift Broadband) are in roll-out	Up to 432 per channel	N/A	FDD	N/A
4	Iridium	Iridium is a constellation of 66 satellites in low Earth orbit providing global telephony services. Both voice and low data rate services are offered.	2.4 kbps full-duplex channels per user	N/A	FDD	N/A
5	GlobalStar	GlobarStar consists of 48 satellites in LEO/MEO orbit. Bent-pipe telephony (voice and data) services are offered in CDMA sub-bands.	Up to 9.6 kbps per user	N/A	FDD	N/A
6	Thuraya	This is a regional mobile satellite system that provides telephony services. It is operated as a private company by the United Arab Emirates with two satellites currently in orbit.	9.6 kbps (per user)	N/A	FDD	N/A
7	IGSAGS	This is a proposed custom satellite concept providing integrated communication, navigation and surveillance services using geostationary satellites. Voice and data would be provided by dividing the DME band into narrow band channels.	30 kbps (per user)	N/A	FDD	N/A
8	HF Data Link	HFDL is a certified data link used to transfer messages between HF (3 to 30 MHz) ground stations and avionics systems on aircraft. Services provided include AOC data link communications.	300 – 1800 bps[19]	N/A	TDD	2.7 kHz[20]
9	Digital Audio Broadcast	This technology includes proprietary satellite services (such as XM radio and Sirius) providing broadcast services. The systems offer approximately 100 channels with data rages of 48 kbps.	48 kbps	N/A	Broadcast only	N/A

3.1.2.5 Custom Narrowband VHF Technologies

This technology family includes standard narrowband VHF systems already developed for AOC, ATS, and/or ATC services and some proposed variants for application to AOC, ATC, and ADS-B services. Three systems are approved as VHF sub-networks through ICAO, including:

- VDL Mode 2 (VDL2): an AOC and ATS data only system
- VDL Mode 3 (VDL3): an ATC system capable of providing both voice and data
- VDL Mode 4 (VDL4): a surveillance data-only system being developed for point-to-point data

Other additional technology candidates in this family are proposed variations to the candidates noted above that incorporate changes in channel spacing or combine select features of the technologies.

A total of five custom narrowband VHF technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–7. Additional descriptive information on these technologies can be found in section 3.6 of the initial technology pre-screening report.[21]

TABLE 3–7.—OVERVIEW OF CUSTOM NARROWBAND VHF TECHNOLOGIES[22]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	VDL Mode 2	This technology is the evolution the ARINC Airborne Communications and Reporting System (ACARS). It is a digital bit-oriented data system that uses a carrier sense multiple access shared data channel. Its primary use is AOC traffic although use for ATC message sets has been proposed.	31.5 kbps (raw); throughput is approx 10 kbps	195 nmi[23]	TDD	25 kHz
2	VDL Mode 3	Based on a physical layer similar to VDL Mode 2, VDL Mode 3 is a TDMA system designed to support ATC voice and data communications. The scheme guarantees controller access through the channel through the use of a management channel carrier control information along with a data channel	31.5 kbps (raw); throughput is 4.8 kbps to approx 12 kbps	185.1 nmi[24]	TDD	25 kHz
3	VDL Mode E	This is an adaptation of the VDL Mode 3 standard that reduces the bandwidth and use of framing for insertion into airspace with 8.33 kHz channel spacing. This provides 6 Mode E channels per 25 kHz DSB-AM channel.	15.75 kbps (raw); throughput is 4.8 kbps	185.1 nmi[25]	TDD	8.33 kHz
4	VDL Mode 4	This technology is based on a data-only broadcast system developed for maritime harbor surveillance applications. The application was adapted for aviation usage, employing a self-organizing TDMA layer through which requested time slots are scheduled by a ground scheduler. Although approved for a surveillance broadcast application, standards are under development for an adaptation providing point-to-point data only communications.	19.2 kbps (raw)	202.5 nmi[26]	TDD	25 kHz
5	E-TDMA	This is a technology that builds on the VDL3 and VDL4 concepts. The concept is based on a cellular ground architecture configuration. A primary focus is the provision of managed Quality-of-Service through-out the service volumes, employing the use of Global Signaling Channels.	Not explicitly defined; assume on the order of 10-12 kbps (similar to Mode 3)	200 nmi[27]	TDD	Not explicitly defined; assume 25 kHz (similar to Modes 3/4)

3.1.2.6 Custom Broadband Technologies

Several proposals have been and continue to be developed to provide wideband solutions for ATS and AOC communication requirements. The candidates considered include those broadband technologies proposed to ICAO ACO WG-C (B-VHF, LDL, L-Band E-TDMA, and ADL); those proposed in response to the NASA RFIs (Flash-OFDM) or suggested by the FAA (UAT and Mode S). These seven candidates are the custom broadband technologies considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–8. Additional descriptive information on these technologies can be found in section 3.7 of the initial technology pre-screening report.[28]

TABLE 3–8.—OVERVIEW OF CUSTOM BROADBAND TECHNOLOGIES[29]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	ADL	The Advanced Airport Data Link (ADL) is a system for the airport environment and includes a data rate of at least 120 kbps per user; large user capacity; airport coverage area, and QoS capability. The system definition includes a multi-carrier CDMA system in C-Band.	2048 kbps	30 nmi[30]	TDD	8192 kHz
2	Flash-OFDM	This technology has been developed for Internet Protocol services between networks and personal computers, focusing on mobility and data communications	3.2 Mbps[31]	4 km[32]	FDD[33]	
3	UAT	This technology was specifically designed for Automatic Dependent Surveillance – Broadcast (ADS-B) application, with simplicity and robustness as design objectives. It operates on a single common wideband channel. Aircraft transmitters transmit one message every second on one of 3200 message start opportunities.	1 Mbps (raw)	200 nmi[34]	TDD	1.17 MHz[35]
4	Mode-S	Mode S is a multi-functional surveillance and communication system that was originally designed as a surveillance improvement for Mode A/C secondary surveillance radar. The 1090 (extended squitter (ES)) operation includes the aircraft broadcast of a data message once per second.	1 Mbps (raw)	100 nmi[36]	TDD	2.6 - 14 MHz[37]
5	B-VHF (MC-CDMA) at L-band	This is a technology based on the MC-CDMA concept providing voice and data dedicated/party-line and broadcast services. The system, based on multi-carrier (OFDM) technology, was initially envisioned as an overlay in the VHF band, but more recently considered as a more likely candidate in L-band	1 – 3 Mbps per MHz BW	200 nmi[38]	FDD or TDD	500 – 2 MHz (to be defined)
6	LDL	This technology is the VDL3 standard with a redesigned physical layer for operation in L-band. The new physical layer has been developed based on the UAT physical layer. Similar to VDL3, a TDMA structure accommodating data (and potentially voice) has been defined.	37.5 to 100 kbps (draft proposal)	268 nmi[39]	TDD	83.33 kHz (proposed)
7	L-Band E-TDMA	This technology is the E-TDMA standard with a redesigned physical layer for operation in L-band.	100 kbps (assumed)[40]	200 nmi (assumed)	TDD	To be defined

3.1.2.7 Military Technologies

The Military Services employ a variety of communication technologies for command and control, situational awareness, and air traffic control. Functionality that is provided by military technologies includes pilot to controller dialog; pilot to pilot dialog; flight information services; air traffic management data exchanges; information downlink; and air-to-air surveillance. Due to their similarity to functional needs of the FRS, military communications were reviewed to identify potential candidates.

Three military technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 3–9. Additional descriptive information on these technologies can be found in section 3.8 of the initial technology pre-screening report.[41]

TABLE 3–9.—OVERVIEW OF MILITARY TECHNOLOGIES[42]

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	Link 16	This is a UHF, frequency hopping (51 frequencies) standard initially designed as a Tactical Data Link system for NATO. The primary mission of the technology is to provide a situational awareness, and command and control voice and data capability.	115 kbps	Up to 300 miles	TDD	3.75 MHz at 3dB points on hopped frequency
2	SINCGARS	SINCGARS is a 2320 25 kHz channel frequency hopped VHF voice and data technology. The technology provides line of sight communications, including data communications in variable message format.	16 kbps	40 km	TDD	25 kHz
3	HAVEQUICK	This technology was initially designed as a voice only system, but has evolved to include a data capability. It is a 7000 25 kHz channel frequency hopped VHF voice and data system. Data communications is accomplished with a modem.	16 kbps	Up to 300 miles	TDD	175 MHz[43]

3.1.2.8 Other Technologies

The final category of technologies denoted "other" includes a single candidate accounting for Airline Passenger Communications (APC). As its name implies, this technology was designed with the goal of accommodating the telephony communication needs of airline passengers. Specific system implementations include Airphone, Aircell, and SkyWay. A summary of key discriminating parameters associated with this candidate technology is provided in table 3–10. Additional descriptive information on these technologies can be found in section 3.9 of the initial technology pre-screening report[44].

TABLE 3–10.—OVERVIEW OF APC TELEPHONY TECHNOLOGY

	Standard	Description	Peak Data Rate	Max Range	Duplexing Approach	Channel Bandwidth
1	APC Telephony	This technology is a FDD circuit voice and data system operating in the 849-851 and 894-896 MHz spectrum.	2.4 Mbps[45]	N/A	FDD	4 kHz[46]

3.2 Defining Screening Thresholds (AHP step 2)

The purpose of step 2 is to define a screening threshold or filter to be applied to the technology inventory to identify in a clear and traceable manner those technologies best suited for the future aeronautical communication environment. This step, shown in context of the entire technology evaluation process, is depicted in figure 3–2.

The selected thresholds are the ability to use protected (safety and regularity of flight) spectrum; the data-loading capability; and the technology-communication range, where specific threshold values for loading and range are traceable to the requirements of the COCR.

A technology that inherently relies on unprotected spectrum (i.e., not in Aeronautical Mobile (Route) Spectrum (AM(R)S) or Aeronautical Mobile Satellite (Route) Spectrum (AMS(R)S)) is considered not a viable candidate for the FRS. Therefore, if a technology is a specific implementation that utilizes unprotected spectrum, the technology was removed from further consideration.

As calculated, the COCR capacity requirements are reflective of all COCR performance requirements. Specifically, the specified data rate requirements are associated with the maximum number of users, with specifications calculated to meet the required QoS while meeting latency requirements.

Additionally, data rate requirements are directly proportional to technology coverage volumes. As such, these parameters were considered to be appropriate selections for the technology screening filter. The data loading threshold was developed from COCR capacity requirements.

Candidate data rate thresholds to consider for the filter were determined upon inspection of the data rate requirements of the COCR. These included sector-based requirements (used for evaluation of terrestrial-based technologies) and per-user requirements (used for evaluation of satellite-based technologies). COCR Phases 1 and 2 data rate requirements were parsed to identify the maximum data rate requirements across all flight domains for ATS-only traffic as well as for ATS and AOC combined traffic loads.[47,48]

The identified sector-based capacity requirements include (see appendix D for COCR requirement tables):

- COCR Phase 1 ATS-only: 7.4 kbps
- COCR Phase 1 ATS and AOC: 25.5 kbps
- COCR Phase 2 ATS-only: 27 kbps
- COCR Phase 2 ATS and AOC: 168.9 kbps

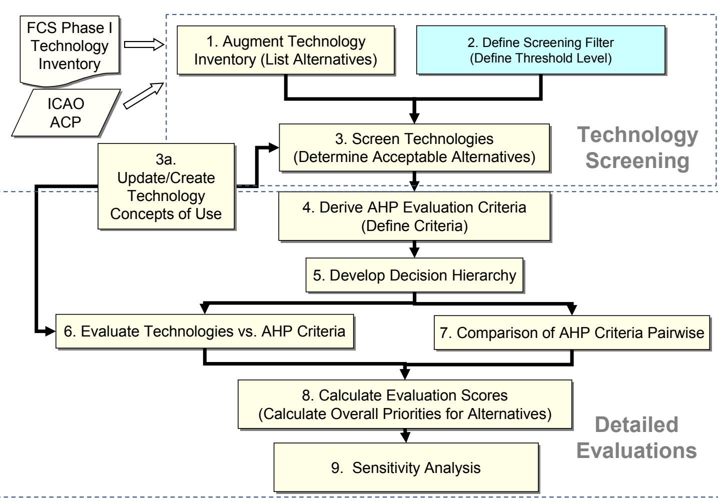


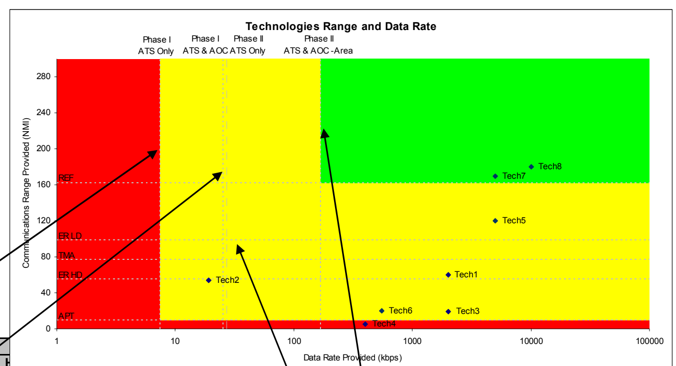
Figure 3–2.—FCS Technology Evaluation AHP—Step 2.

These values were plotted as reference lines on a graph used to build a graphical visualization of the screening threshold. For the data loading capability and technology communication range metrics, specific threshold values traceable to the requirements of the COCR were defined. Maximum data loading thresholds were defined for air traffic services (ATS) alone and for ATS and airline operational control (AOC) in both the near term (COCR Phase 1) and the far term (COCR Phase 2). Communication range thresholds were defined for airport surface (APT), en route high density (ER HD), terminal maneuvering area (TMA), en route low density (ER LD), and a reference threshold that represents the radio horizon for FL180 (REF). In addition to these reference lines, red/yellow/green shading was applied to provide a means to visualize which technologies would be able to meet all specified requirements (i.e., provides capacity greater than the COCR Phase 2 ATS and AOC requirements); or has potential to provide a role in future aeronautical communications (i.e., capacity is, at a minimum, greater than COCR Phase 1 ATS-only requirements). A depiction of the reference capacity requirements (for terrestrial technologies) is provided in figure 3–3.

Note in figure 3–3, red shading is applied to data rates below the COCR Phase 1 ATS-only capacity requirement (7.4 kbps); yellow shading is applied to data rates between the COCR Phase 1 ATS-only capacity requirement and COCR Phase 2 ATS and AOC capacity requirement; and green shading is applied to data rates above the COCR Phase 2 ATS and AOC capacity requirements. Note that the shading corresponding to the vertical axis values relates to the reference range thresholds discussed below.

The identified COCR per-user data capacity requirements include (see appendix D for COCR requirement tables):

- COCR Phase 1 ATS-only: 2.5 kbps per user
- COCR Phase 1 ATS and AOC: 4.3 kbps per user
- COCR Phase 2 ATS-only: 19.7 kbps per user
- COCR Phase 2 ATS and AOC: 28.7 kbps per user



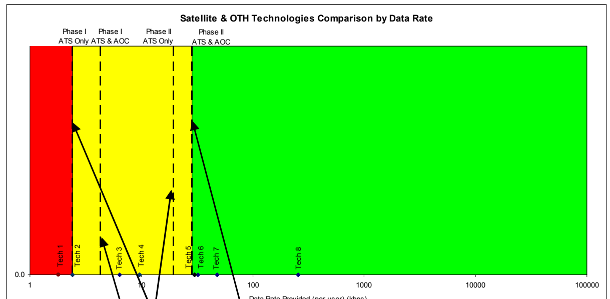
PHASE 1		Airport SV		TMA SV						
		HD	LD	HD	LD					
Separate ATS	UL	4.0	1.2	2.3	2.2	1.2	1.5	1.2	0.3	0.3
	DL	4.3	1.9	4.1	3.9	3.7	4.9	3.7	2.7	2.2
	UL&DL	7.4	2.0	5.3	5.0	4.1	5.6	4.1	2.8	2.2
Separate AOC	UL	15.6	2.7	0.3	0.3	8.6	11.9	8.6	3.3	2.8
	DL	3.5	0.7	0.8	0.8	0.8	1.3	0.8	0.4	0.3
	UL&DL	19.9	2.9	0.8	0.8	9.1	13.8	9.1	3.3	2.8
Combined ATS&AOC	UL	18.4	2.9	2.3	2.2	9.0	12.7	8.9	3.3	2.8
	DL	6.7	2.0	4.3	4.1	3.8	5.2	3.8	2.7	2.2
	UL&DL	25.5	3.3	5.6	5.3	11.4	17.7	11.3	4.5	3.4

Table 6-19: Air/Ground Capacity Requiremen

PHASE 2		Airport SV		TMA SV AEXEC		ER SV AEXEC			OR SV AEXEC		Auto Op
		HD	LD	HD	LD	HD EU	HD US	LD	HD	LD	Area
Separate ATS	UL	12.8	7.1	22.0	22.2	20.9	22.4	21.0	19.8	19.6	7.1
	DL	11.3	5.2	10.3	10.7	9.8	13.5	10.5	8.5	8.3	13.3
	UL&DL	19.6	7.3	24.5	25.1	23.5	27.0	24.0	20.3	19.9	13.6
Separate AOC	UL	113.0	14.1	0.3	0.2	52.4	96.1	64.1	24.0	18.2	56.2
	DL	6.7	1.2	2.4	2.2	1.4	2.7	1.8	0.6	0.4	1.1
	UL&DL	131.2	14.1	2.6	2.3	58.6	106.9	72.6	24.4	18.2	62.8
Combined ATS&AOC	UL	120.0	24.6	22.0	22.2	119.1	168.3	134.8	82.1	62.8	76.7
	DL	13.4	5.4	11.1	11.8	10.2	13.9	10.9	8.6	8.3	13.4
	UL&DL	144.3	24.8	25.2	25.8	119.4	168.9	135.2	82.2	62.9	80.5

Table 6-20: Air/Ground Capacity Requirements (kbps) – Phase 2

Figure 3–3.—Reference Sector-Based Capacity Requirements for Technology Screening.



PHASE 1		Airport SV		TMA SV		En Route	ORP
		Dep	Arr	Dep	Arr	SV	SV
Separate ATS	UL	1.1	0.7	0.6	1.5	0.9	0.3
	DL	1.8	0.7	1.9	0.8	2.4	1.7
	UL&DL	1.8	0.7	2.0	1.5	2.5	1.7
Separate AOC	UL	2.4	0.2	0.2	0.2	4.3	2.4
	DL	0.3	0.3	0.3	0.3	0.3	0.3
	UL&DL	2.4	0.3	0.3	0.3	4.3	2.4
Combined ATS&AOC	UL	2.4	0.7	0.6	1.5	4.3	2.4
	DL	1.8	0.7	1.9	0.8	2.5	1.7
	UL&DL	2.4	0.7	2.0	1.5	4.3	2.5

Table 6-22: Air/Ground C

PHASE 2		Airport SV		TMA SV		En Route	ORP	AOA
		Dep	Arr	Dep	Arr	SV	SV	
Separate ATS	UL	6.9	1.8	19.5	19.5	19.5	19.4	6.7
	DL	6.2	1.9	6.8	3.3	6.7	8.5	12.5
	UL&DL	6.9	1.9	19.7	19.5	19.5	19.5	12.5
Separate AOC	UL	9.2	0.2	0.2	0.2	20.4	12.1	12.6
	DL	0.3	0.3	0.4	0.4	0.3	0.3	0.3
	UL&DL	9.2	0.3	0.4	0.4	20.4	12.1	12.6
Combined ATS&AOC	UL	9.2	1.8	19.5	19.5	28.6	25.4	12.7
	DL	6.2	1.9	6.8	3.4	6.7	8.5	12.5
	UL&DL	9.5	1.9	19.8	19.5	28.7	25.4	17.0

Table 6-23: Air/Ground Capacity Requirements (kbps) for Each Aircraft usign A Separate 'Channel' – Phase 2

Figure 3–4.—Reference Per-User Capacity Requirements for Technology Screening.

Similar to the screening filter graph created for evaluation of terrestrial-based technologies, these values were plotted as reference lines on a graph. Red/yellow/green shading was applied to provide a means to visualize those technologies that would meet all specified requirements (i.e., provide per-user capacity greater than the COCR Phase 2 ATS and AOC per-user requirements); or has potential to provide a role in future aeronautical communications (i.e., per-user capacity is, at a minimum, greater than COCR Phase 1 ATS-only per-user requirements). A depiction of the reference capacity requirements for satellite-based (and over horizon) technologies is provided in figure 3–4.

Note that in figure 3–4, the graphical depiction of the screening threshold for satellite-based-technologies-only includes the capacity threshold (and not the range threshold). This is because communication range does not provide a meaningful discriminator for satellite and over-horizon technologies.

For terrestrial-based technologies, five communication range reference values were captured for the screening filter. These included airport range; terminal maneuvering area (TMA) range; low density en route range; high-density en route range, and radio horizon reference range. Specific values of required communication range for airport, TMA, and en route environments were derived from information provided in the COCR. Specifically, domain description information of the COCR was used to calculate the maximum communication range for each flight domain assuming a worst-case transmitter location (i.e., on the edge of the coverage volume).

For the airport domain, the maximum communication range was calculated to be approximately nine nautical miles (nmi.), as shown in figure 3–5.

For the TMA flight domain, COCR Phase 2 sector volume information provided in section 7 of the COCR was used to estimate the TMA volume and corresponding maximum communication range requirements. The maximum coverage range for the TMA was calculated to be 76.7 nmi, as shown in figure 3–6.

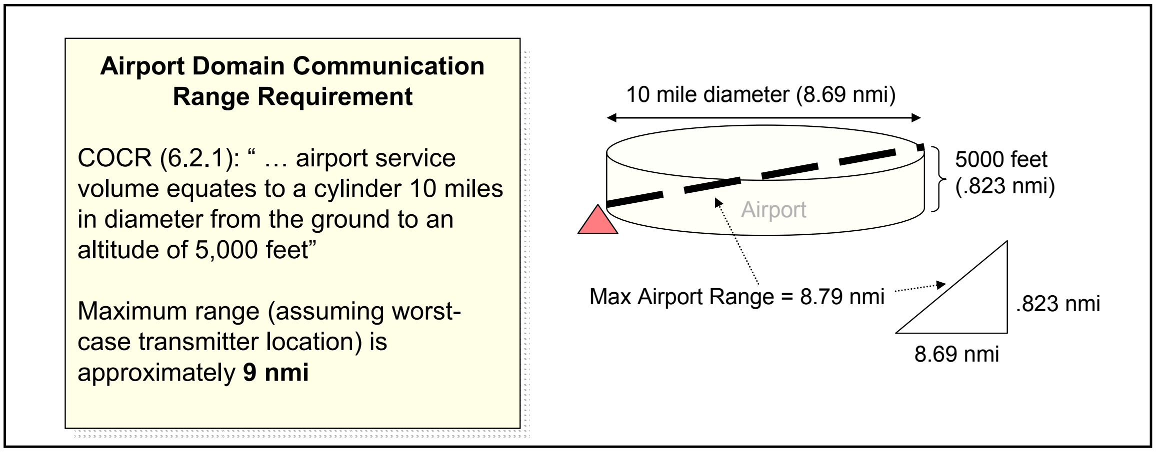


Figure 3–5.—Calculating Airport Communication Range Requirement.

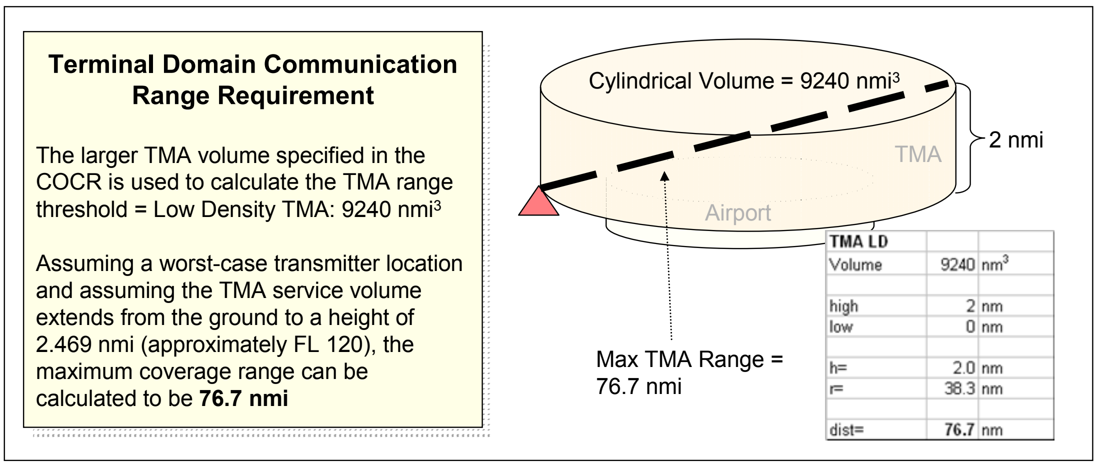


Figure 3–6.—Calculating TMA Communication Range Requirement.

The COCR Phase 2 sector volume information provided in the COCR was again used to estimate the en route service volumes (for low- and high-density (HD) volumes) and corresponding maximum communication range requirements. The maximum coverage range for the high-density (HD) en route service volume was calculated to be 54.5 nmi., while the maximum range required for the low-density (LD) en route service volume is 98.1 nmi., as shown in figure 3–7.

The final communication range reference considered was the radio horizon reference range. This reference is meaningful as some sector sizes and corresponding range requirements may exist other than those defined above. The reference horizon range was calculated for flight level 180. To account for signal refracting towards the Earth (especially at VHF and Ultra-High Frequency (UHF)), the approximation used for the radio horizon equation is Distance (nmi) = SQRT (2 * height (feet)). For the reference height of 18 000 ft, this value is 164.8 nmi.

Similar to the data capacity reference values, the range reference values were plotted on the terrestrial-based technology screening filter graph. Range values that exceeded all domain-specific derived range requirements and the radio horizon range were colored with green shading; values that could not meet the minimum communication range requirement (i.e., airport domain range requirement) and therefore have minimum applicability to the aeronautical environment were shaded red; and all values in-between shaded yellow. A visualization of the range reference values is provided in figure 3–8.

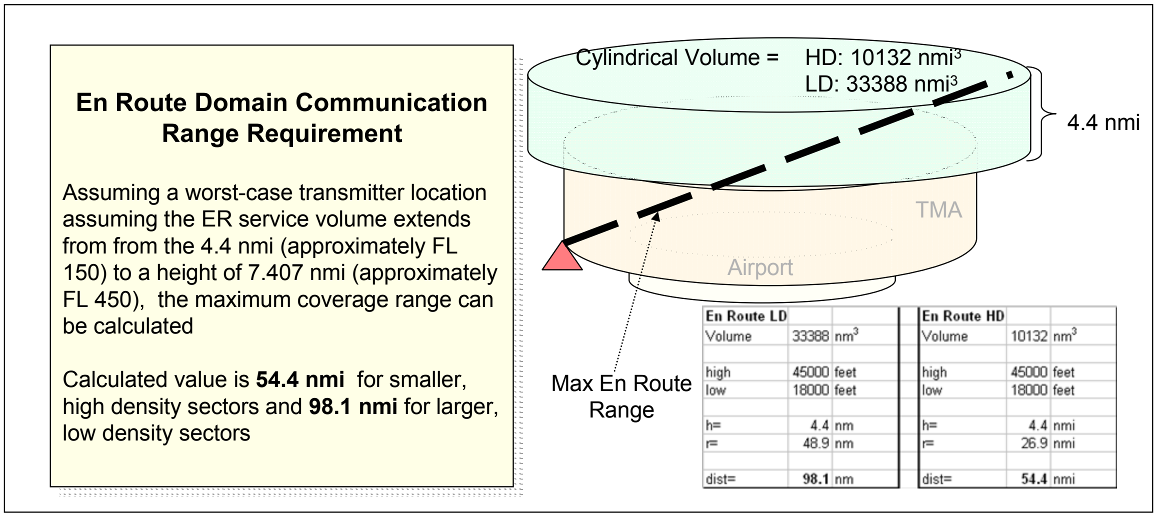


Figure 3–7.—Calculating En Route Communication Range Requirements.

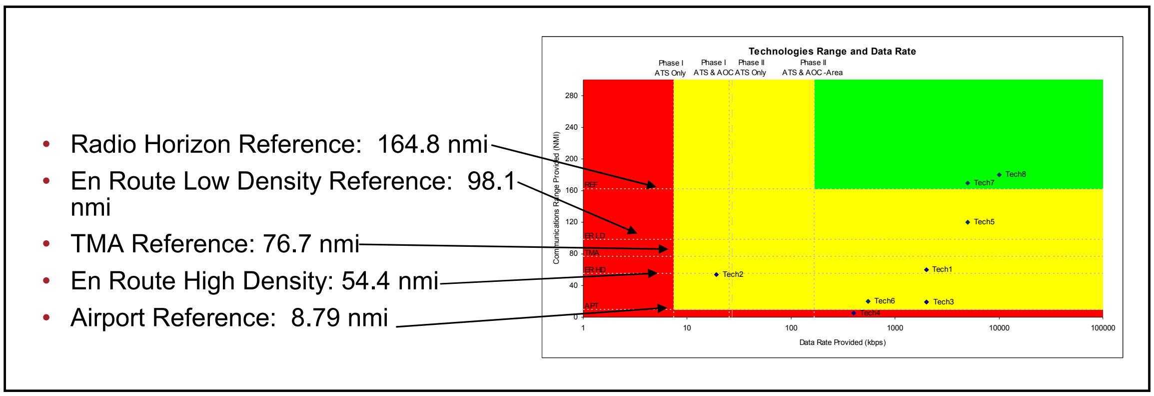


Figure 3–8.—Communication Range Reference Values.

3.3 Screen Technologies

Having defined the technology screening filter, the next step was to apply the filter to screen technologies. A first step in the screening was to identify those technologies that inherently rely on unprotected spectrum and remove them from consideration. The technologies removed from further consideration based on this screening step included Connexion, GlobalStar, Digital Audio Broadcast, and APC Telephony.

The next step in the screening was to consider technology performance compared to required data capacity and range requirements (from the COCR). To perform this part of the screening, a general understanding of how each technology would be applied to the aeronautical environment was required. This type of information was captured in a concept of use for each technology. Based on the concept of use, the screening filter was then applied to terrestrial-and satellite-based technologies. The following sections describe the concept of use defined for technologies under consideration; application of the data capacity and range screening filter; and discussion of results (recommended technologies and comparison to similar screening efforts).

3.3.1 Define Technology Concept of Use

Many technologies offer a range of service and configuration options. To support the technology screening and detailed evaluation, each technology was reviewed to identify the applicable configuration

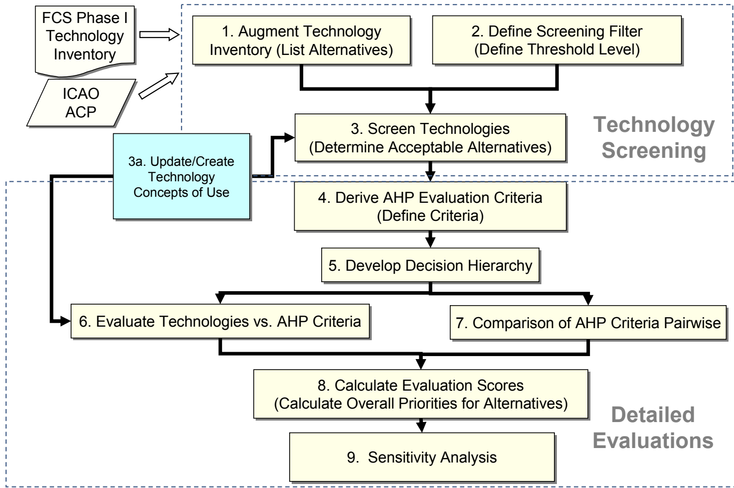


Figure 3–9.—FCS Technology Evaluation AHP—Step 3A.

for provision of aeronautical data-link communications and associated key performance parameters. This step in the evaluation process (step 3A) is shown in context in figure 3–9.

A description of the concept of use for a majority of the technologies is provided in the technology Pre-Screening report.[49] For the three technologies added to the original technology inventory, concept of use material is provided in appendix B. A set of key concept of use parameters summarized for each technology is captured in the table 3–11.

TABLE 3–11.—SUMMARY OF TECHNOLOGY CONCEPT OF USE PARAMETERS FOR SCREENING

Technology	Data Capacity (kbps)	Comm Range (nmi)	Operational Configuration and Notes
1. W-CDMA(US)/ UMTS FDD (Eur)	960[50]	162[51]	In general this technology is considered for deployment in the DME band. The concept of use for cellular services assumes the use of packet data services.
2. TD-CDMA(US)/ UMTS TDD (Eur)	2000[52]	16.2[53]	
3. CDMA2000 3x	460.8[54]	54[55]	
4. CDMA 1xEV	153.6[56]	54[57]	
5. GSM/GPRS/ EDGE	400[58]	18.9[59]	
6. TD-SCDMA	2000[60]	16.2[61]	
7. DECT	552[62]	0.2[63]	
8. IEEE 802.11	54000[64]	0.54[65]	For the IEEE 802 family, the applicable aeronautical frequency band is specified to be the MLS band; it can accommodate wideband signals and is within the design range of both 802.16 and 802.11 standards. Due to short design range and support for low-speed mobile platforms, 802.11 and 802.16 limited to consideration for the airport domain. Applicable bearer services include Unsolicited Grant Service and Real-Time Poling Service
9. IEEE 802.15	55000[66]	.005[67]	
10. IEEE 802.16	13800[68]	19.9[69]	
11. IEEE 802.20	2000[70]	24.3[71]	
12. APCO P25	9.6[72]	18.9[73]	Public safety technology candidates are considered in the context of the L-Band aeronautical spectrum. Specific services applicable to the FRS varied some with technology specific offerings, but all included packet data services. For P34, two physical layer standards are available. The IOTA physical layer standard was selected for this application[74]
13. TETRA Release 1	30.375[75]	9.5[76]	
14. TETRAPOL	8[77]	15.1[78]	
15. IDRA	64[79]	21.6[80]	
16. iDEN™	64[81]	21.6[82]	
17. EDACS	9.6[83]	160[84]	
18. APCO P34	173[85]	162[86]	

Technology	Data Capacity (kbps)	Comm Range (nmi)	Operational Configuration and Notes
19. TETRA Release 2 (TAPS)	473[87]	2.7[88]	
20. TETRA Release 2 (TEDS)	691[89]	2.7[90]	
21. Custom Satellite System (e.g. SDLS)[91]	30 (per user)[92]	N/A	When formulating concepts of use for satellite systems, several issues were noted. These include the need to investigate provisioned availability; the possible constraints associated with expensive, heavy, and high-power consumption satellite avionics; and call setup times. For the satellite systems, the concepts of use generally follow close to use concepts offered to existing mobile users. An exception is the Inmarsat where concept that included uplink to the satellite from the ATC facility on a L-band connection (e.g. as a fixed mobile) was proposed.[93] A similar architecture was proposed for consideration for the Iridium candidate.[94]
21. Inmarsat Swift Broadband	32 (per user – QoS low end); 256 (per user – QoS high end)[95]	N/A	
23. Iridium	2.4 (per user)[96]	N/A	
24. Thuraya	9.6 (per user)[97]	N/A	
25. IGSAGS	30 (per user)[98]	N/A	
26. HF Data Link	1.8 (per user)[99]	N/A	
27. VDL Mode 2	10[100]	195[101]	The custom narrowband technologies were each designed for the needs of aviation and thus provide an array of connection-oriented and connection-less services. The focus on this study is on the data services provided. As such, the focus for VDL3 is the 3T service.
28. VDL Mode 3	14.4[102]	185.1[103]	
29. VDL Mode E	4.8[104]	185.1[105]	
30. VDL Mode 4	14.4[106]	202.5[107]	
31. E-TDMA	14.4[108]	200[109]	
32. ADL	2048[110]	30[111]	This family addresses a range of wideband technologies; some are currently implemented to provide aeronautical surveillance services; others are specific to wireless commercial standards and yet others are proposed custom solutions for meeting the needs of aviation. It should be noted that UAT and Mode S cannot support addressed data and thus their concept of use is limited to broadcast applications. For LDL, assume a data-only configuration (i.e. mode 5T)
33. Flash-OFDM	3200[112]	2.2[113]	
34. UAT	3.712[114] (per user)	200[115]	
35. Mode-S	0.112 [116] (per user)	100[117]	
36. B-VHF (MC-CDMA) (at L-Band)	421.2[118]	200[119]	
37. LDL	100[120]	268[121]	
38. L-Band E-TDMA	100[122]	200[123]	
39. Link 16	115[124]	260.7[125]	The military technologies provide many services that are similar to the functional needs of an ATS communication system. For Link 16, dedicated access was selected as the slot assignment concept for the FRS; additionally, the P4SP data packing structure was identified for the concept of use.
40. SINCGARS	16[126]	21.6[127]	
41. HAVEQUICK	16[128]	260.7[129]	

3.3.2 Compare Technologies Versus Screening Metrics (AHP Step 3)

Based on the information defined in the technology concepts of use, the screening filter was applied to the technologies first on a technology family basis and second, to an entire population of technology candidates. This step in the AHP process, step 3, is shown in context of the entire evaluation process in figure 3–10.

Results for both screening on a technology family basis as well as screening of the entire population of technologies are provided below.

Application of the screening filter to the cellular derivatives technology family is shown in figure 3–11.

All technologies within the cellular family perform well with respect to offered capacity. However, many of the technologies have very small communication range capability. The technologies with limited

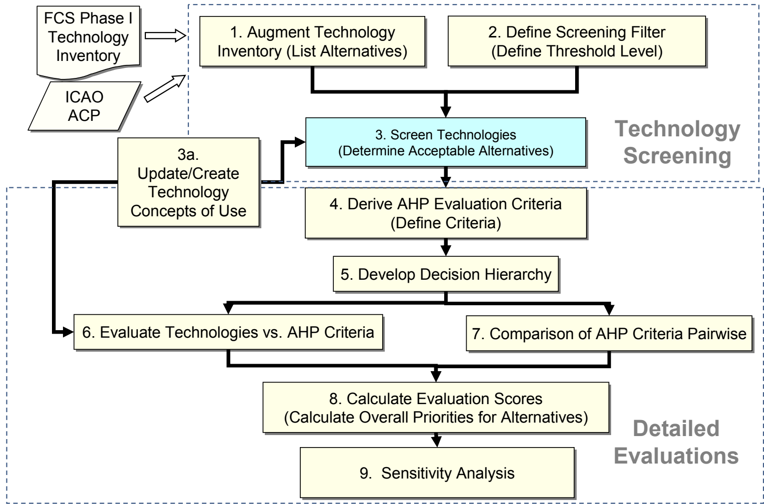


Figure 3–10.—FCS Technology Evaluation AHP—Step 3.

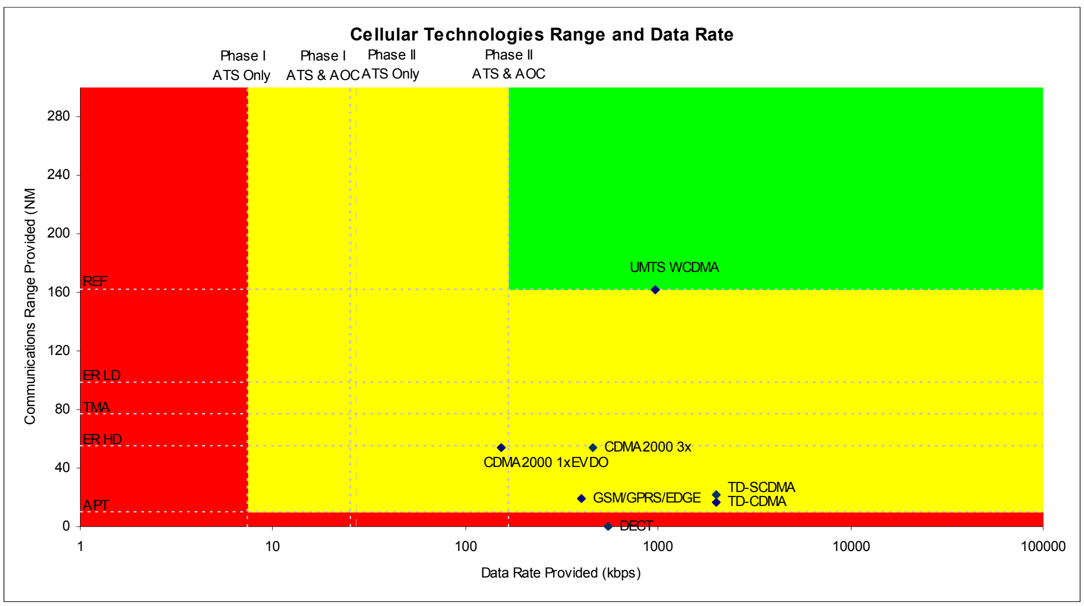


Figure 3–11.—Technology Screening for Cellular Derivative Technologies.

range performance would only be applicable to the future communication systems as cost-effective solutions in the airport domain. As a result, only UMTS W-CDMA is considered a viable candidate for a general aeronautical communication solution.

Similar to the cellular technology family, the IEEE 802 technologies perform well with respect to offered capacity. However, there are no technologies within this family that provide sufficient range to be considered a general aeronautical communication solution. The result of the application of the screening filter to these technologies is shown in figure 3–12. These technologies can only be considered as viable solutions within the context of the airport domain.

The next set of technologies considered is the Public Safety Radio (PSR) technology family. Results of the screening filter applied to this family are shown in figure 3–13.

A large number of technologies within this family perform well with respect to offered capacity. However, similar to the previous technology family results, the technologies have very small communication range definitions. EDACS can provide sufficient communication range performance, but

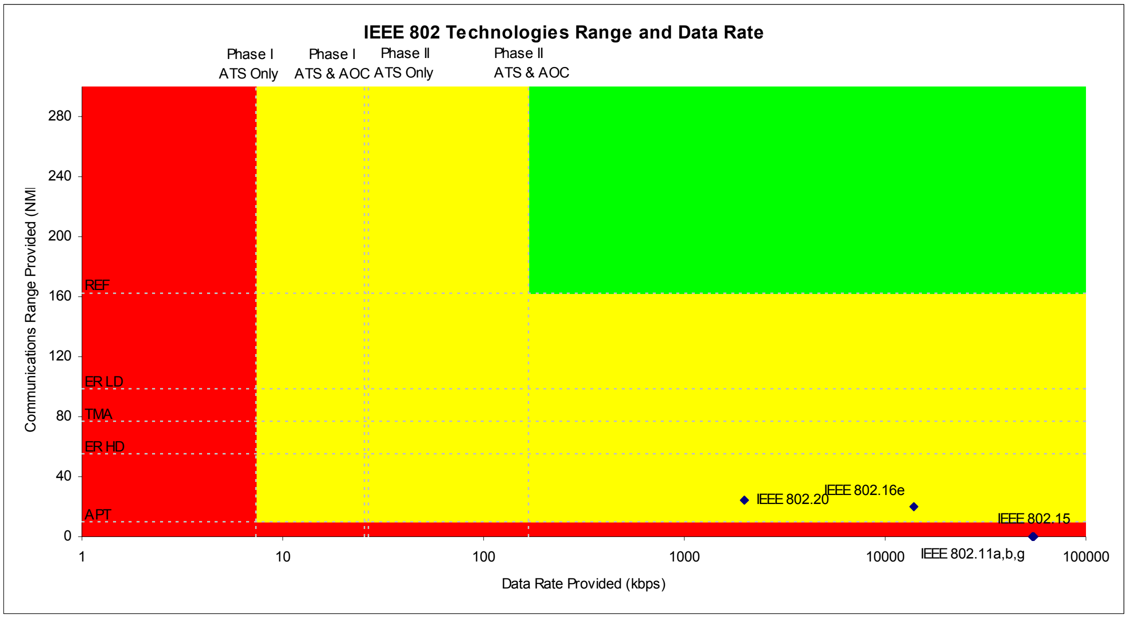


Figure 3–12.—Technology Screening for the IEEE 802 Technologies.

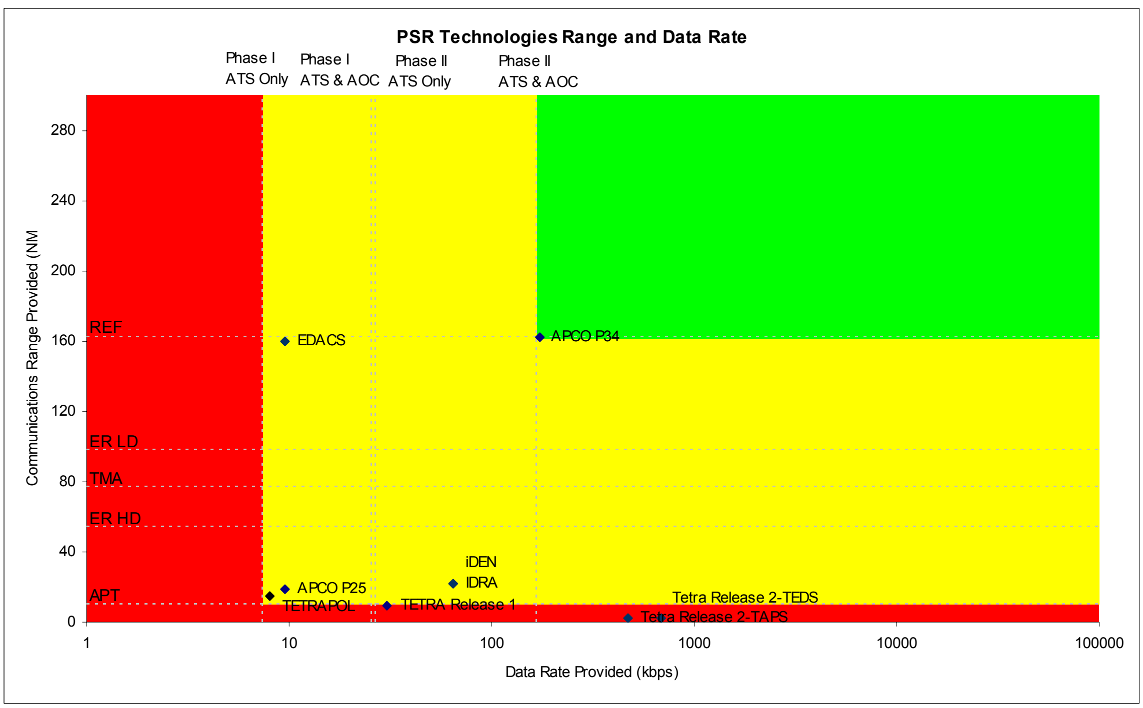


Figure 3–13.—Technology Screening for PSR Technologies.

the offered data rate is only slightly above the minimum COCR Phase 1 requirements. APCO P34 is a viable candidate as a general aeronautical communication solution as it offers sufficient data capacity and communication range performance to be considered a long-term solution.

Two categories of custom solutions are considered. The first is the custom narrowband VHF technologies. The result of the application of the screening filter to this family is provided in figure 3–14. All technologies within this family provide sufficient communication range to be considered cost-effective general aeronautical communication solutions. Although many of these technologies provide

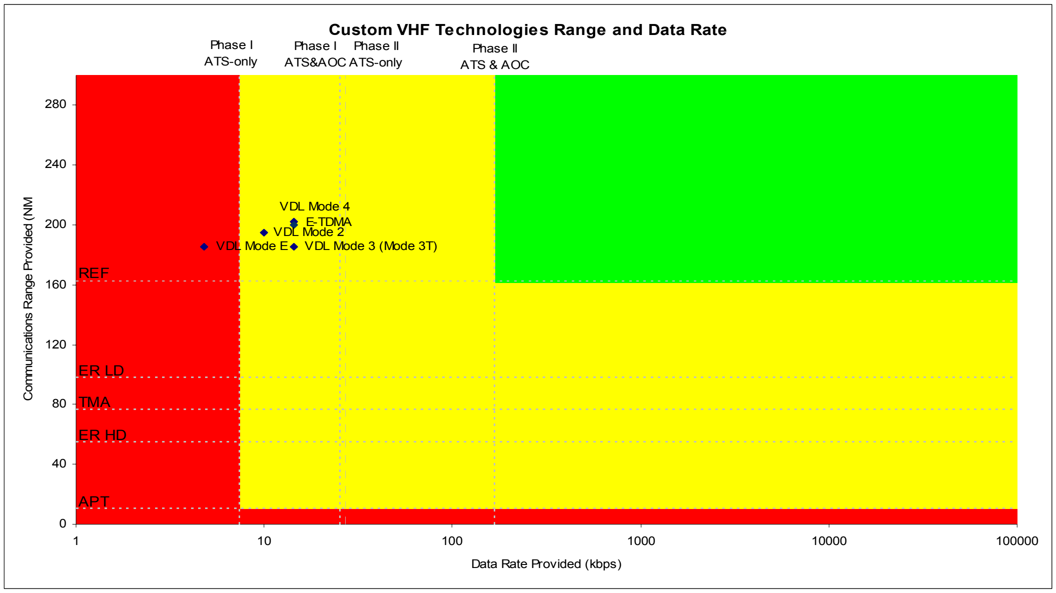


Figure 3–14.—Technology Screening for Narrowband VHF Technologies.

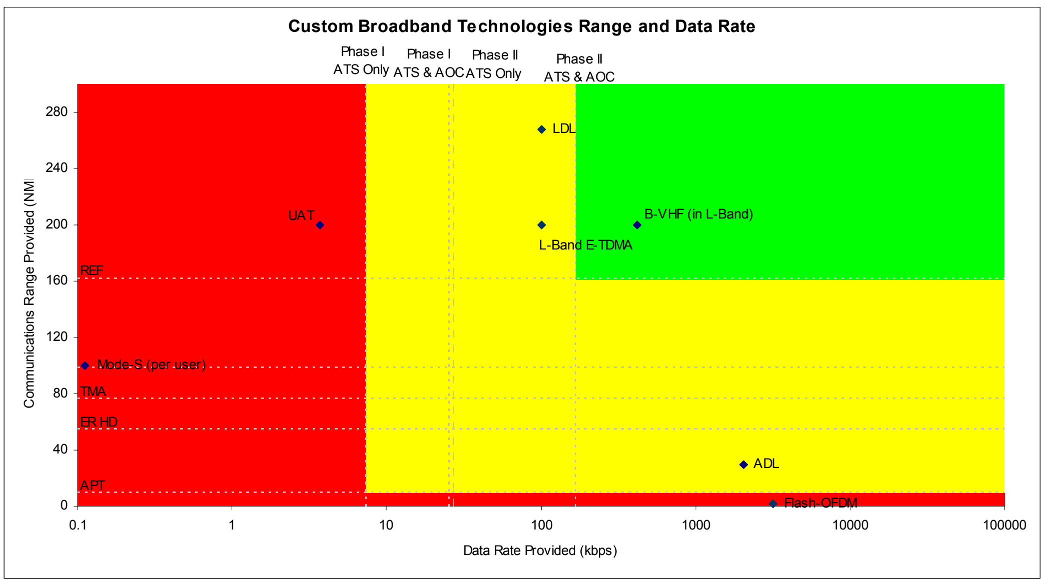


Figure 3–15.—Technology Screening for Custom Broadband Technologies.

sufficient data capacity to accommodate COCR Phase 1 capacity requirements, none can accommodate COCR Phase 2 requirements, even for ATS-only traffic. Since the FAA roadmap indicates that the United States will only field the FRS as a consequence of insufficient data rate of VHF technologies and this system will persist through COCR Phase 2 operating concepts, it did not seem appropriate to bring forward any of these technology candidates from the technology screening.

The second set of custom technology solutions includes the custom broadband technologies. These technologies are considered in the context of application in the L-Band. Technology screening results for this family are shown in figure 3–15.

Within the custom broadband technologies, there are two general categories of results. LDL, L-Band E-TDMA, and B-VHF (at L-Band) all provide or come close to providing all required data rates. B-VHF (at L-Band) meets all requirements, while LDL and L-Band E-TDMA exceed COCR Phase 2 ATS-only requirements. All provide sufficient communication range to be considered viable general communication solutions. The second category of results is technologies that only scored well against either data capacity or range. These technologies, UAT, Mode S, Flash-OFDM, and ADL, are not considered viable general communication solution technologies due to poor performance in either data rate or range. (Note to the reader: the data rates that are plotted for UAT and Mode S are effective rates, not the modulation rate.)

The next set of evaluated technologies includes those within the military technology family. Results for screening of this technology family are shown in figure 3–16. SINGARS does not offer sufficient data capacity or range to be considered a viable general communication solution candidate. HAVEQUICK can accommodate the required communication range, but has insufficient data capacity to meet ATS-only requirements for COCR Phase 2 operations. Link 16 performs well in both data rate and communication range. This technology exceeds all communication range references, meets Phase 2 ATS-only data capacity requirements, and comes close to meeting all data capacity requirements. It is recommended as a technology for further consideration.

The final technology family to be screened includes the satellite and over-horizon technologies. Recall that only the data capacity screening applies to this family. Screening results for this family are shown in figure 3–17.

Inmarsat Swift Broadband (SBB) and the Custom Satellite System meet all of the per-user data rate requirements for both COCR Phase 2 ATS-only traffic and COCR Phase 2 ATS and AOC combined traffic. Although some other candidates in this family meet COCR Phase 1 requirements, they do not provide sufficient capacity to provide the required per-user capacity to meet COCR Phase 2 ATS-only requirements and therefore have limited applicability to COCR Phase 2. Inmarsat SBB and the Custom Satellite System are the technologies brought forward from the screening of this technology family.

A summary of the technology screening filter applied to all technologies together is shown in figure 3–18. Note that on this graphic, the terrestrial-based technologies color coding is adopted. Satellite and over-horizon technologies are also plotted on the same graphic for completeness, but noted capacity values are "per-user." Thus, the acceptable satellite technologies (i.e., Inmarsat SBB and the Custom Satellite System) account for the technologies identified on the graph as candidates to bring forward, but which are seemingly in the unacceptable (red) performance area.

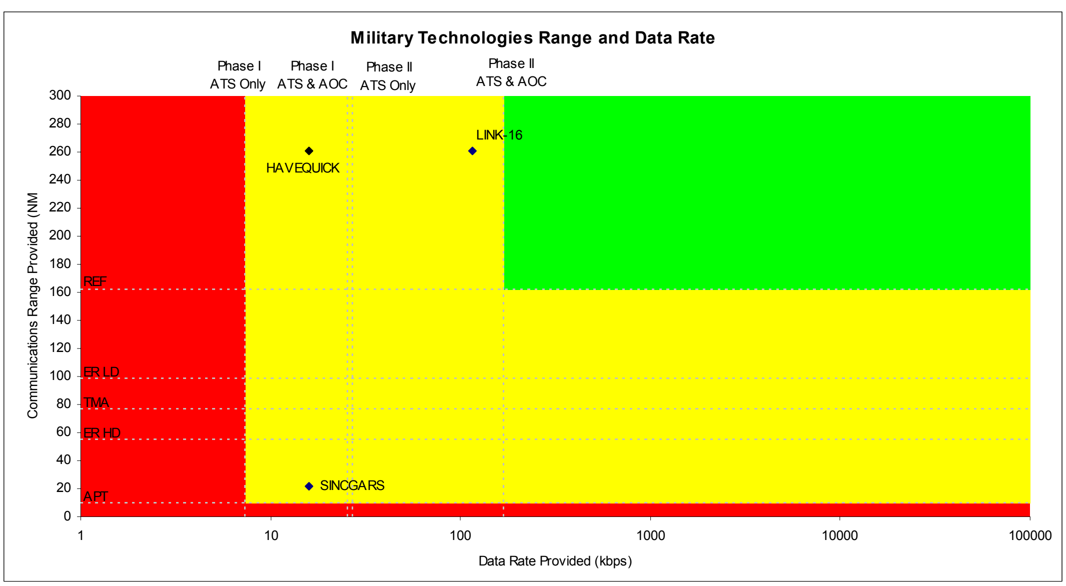


Figure 3–16.—Technology Screening for Military Technologies.

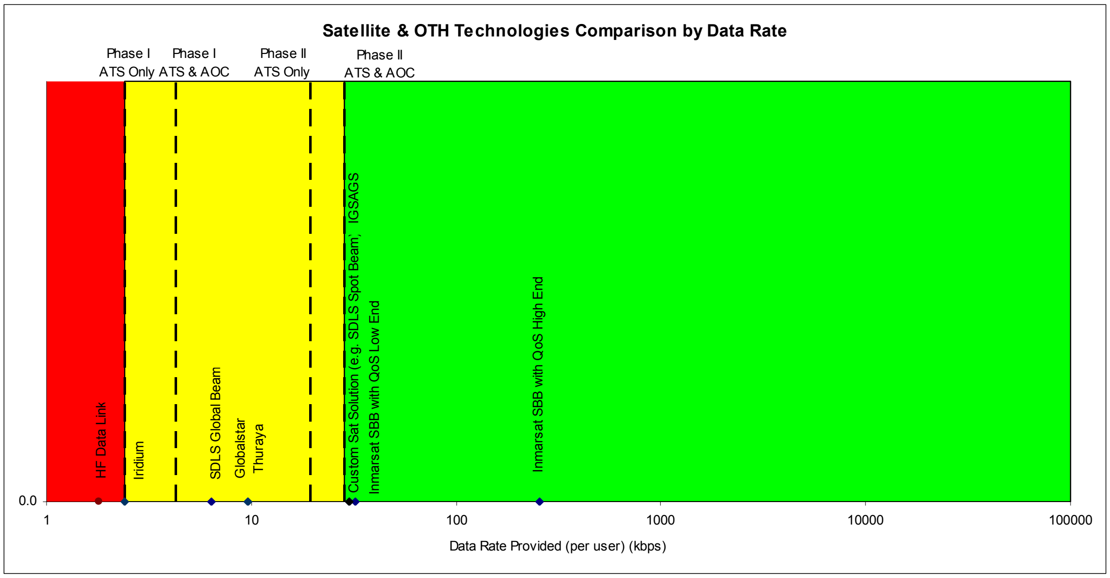


Figure 3–17.—Technology Screening for Satellite and Over-Horizon Technologies.

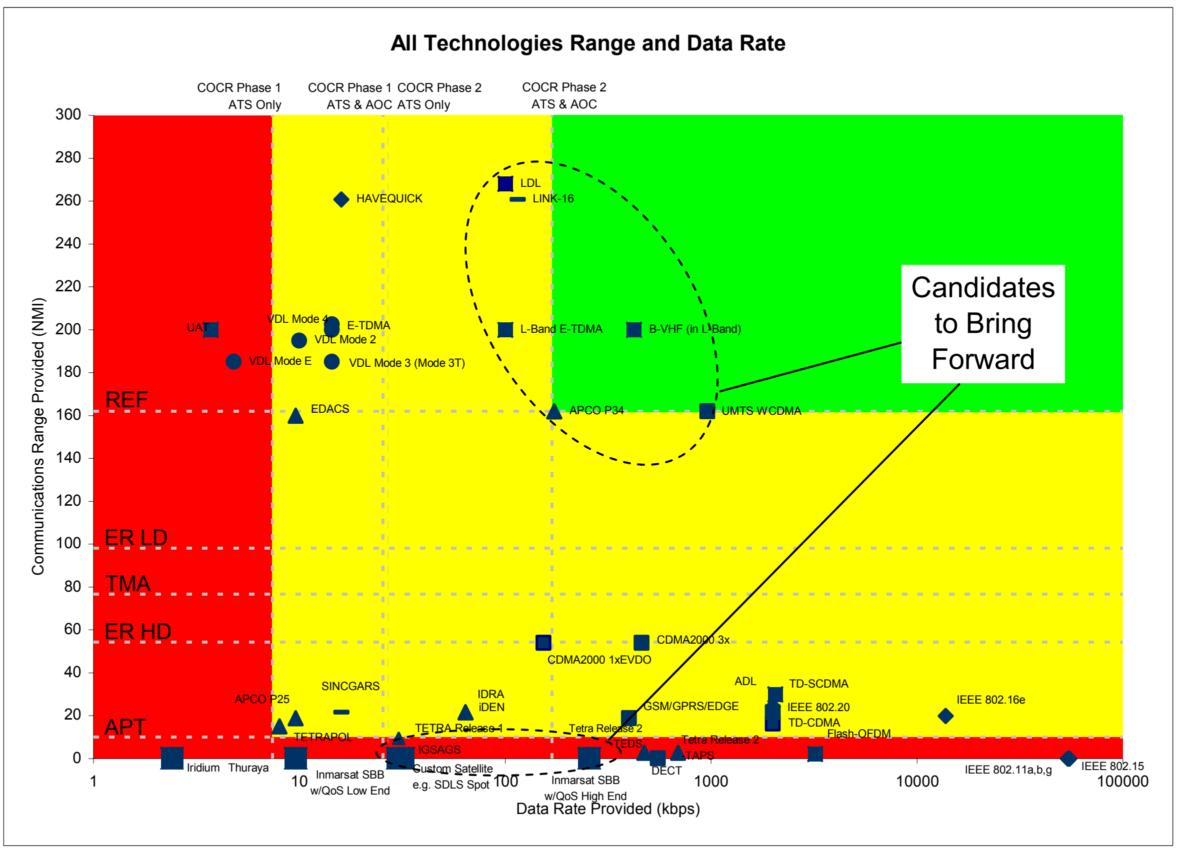


Figure 3–18.—Technology Screening Summary.

On the graphic above, candidates recommended to bring forward from the screening process are identified. Upon initial evaluation, each of the recommended candidates provides data capacity to, at a minimum, meet COCR Phase 2 ATS-only requirements. Additionally, each terrestrial-based candidate provides sufficient communication range to meet all derived range requirements, with most providing radio horizon coverage. The performance of these recommended technologies will be further validated through detailed technology evaluations.

3.3.3 Recommended Technology Shortlist and Comparison to EUROCONTROL Screening

As a result of the technology screening process described in section 3.3.2, eight technologies have been identified as candidates for a general aeronautical communication solution for the FRS (also called a continental solution because the solution applies to all continental flight domains including airport, terminal, and en route). In addition, some additional technologies have been identified as best performers in the context of specific flight domains that have a unique environment and may warrant separate technology consideration (i.e., oceanic and airport domains). A summary of the recommended technologies results from the technology screening has been deemed the "technology short-list." These recommendations are summarized in table 3–12.

TABLE 3–12.—RECOMMENDED TECHNOLOGIES FROM TECHNOLOGY SCREENING

	Technology Short-List
Continental Solution	W-CDMA P34 Inmarsat SBB Custom Satellite Solution E-TDMA LDL B-VHF (at L-band) Link 16
Oceanic Domain	Inmarsat SBB Custom Satellite System
Airport Domain	IEEE 802.16

For the airport domain, candidate applicable technologies include those from the cellular and 802 technology families. Of the candidates in those families that meet the requirements for the airport, appears to be the most applicable. Reference the cellular and 802 family concepts of use for additional information.

It is instructive and informative to compare the current screening results to the technology short-list considered by EUROCONTROL. In March 2007, EUROCONTROL presented its current technology shortlist at the ICAO ACP WG-C10 meeting.[130] Its complete technology short-list is provided in table 3–13.

TABLE 3–13.—EUROCONTROL TECHNOLOGY SHORT LIST FROM ICAO ACP WG-C10 (MARCH 2006)

	Technology Short-List
Evolution of existing aeronautical systems or concepts	• (x) DL3 • E-TDMA • (x) DL4
New Terrestrial Systems	• B-VHF • 3G Systems (WCDMA) • P34
Satellite Systems	• Inmarsat SwiftBroadband • New Satellite System
Airport/Surface Systems	• 802.16 derivatives .11x, .16 and .20 • Airport Data Link

Although the organization of the EUROCONTROL results is slightly different from the results of the screening presented in this report, a direct comparison of results can be made. This comparison is provided in figure 3–19. This comparison shows a significant overlap in recommendations for the "short-list" of technologies to consider for the FRS. This overlap is significant as member participants of the FCS and the ICAO Aeronautical Communication Panel work towards harmonized technology solutions for the future communication infrastructure.

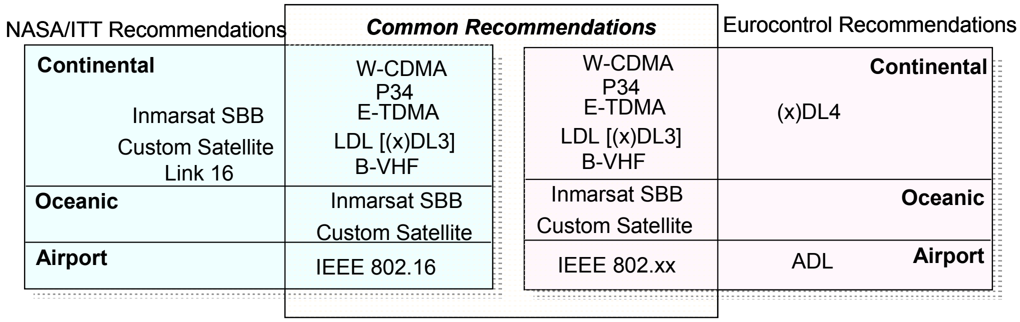


Figure 3–19.—Comparison of Current Technology Screening Results to EUROCONTROL Technology Short-List.

4. PRELIMINARY DETAILED TECHNOLOGY EVALUATION

This section of the report describes the work performed to derive technology evaluation criteria; organize criteria into evaluation decision factors; evaluate technologies against the criteria/decision factors; weight the decision factors and score technologies. It should be noted that the weighting of decision factors and scoring of technologies are preliminary results in this phase of the FCS. They represent the initial implementation of the AHP that included only a streamlined execution of steps 5 to 9 supporting proof-of-concept of the AHP methodology. The results, therefore, can be considered only preliminary at this time. A second and full iteration of the complete detailed evaluation process (steps 5 to 9) will be performed as part of the third and final technology study component of the FCS. Final results, including a final technology recommendation, are expected at the completion of the FCS. The work to develop evaluation criteria, and a preliminary application of the AHP to score technologies, is documented in the following subsections:

- Develop Evaluation Criteria (AHP step 4)—Section 4.1
- Organize Criteria into Decision Factors (AHP step 5)—Section 4.2
- Evaluate Technologies (AHP Step 6)—Section 4.3
- Weight Decision Factors (AHP Step 7)—Section 4.4
- Compute Preliminary Technology Scores (AHP Steps 8 and 9)—Section 4.5

4.1 Evaluation Criteria Development (AHP step 4)

The development of evaluation criteria is the first AHP process step supporting detailed technology investigation, as shown in figure 4–1.

A structured analysis of the COCR was undertaken to derive a set of evaluation criteria that would be directly traceable to the COCR. During the process of developing these criteria, it was discovered that this process would only yield what could be considered the technical-evaluation criteria. An equally important set of criteria that address strategic objectives of a future aeronautical communication system, termed institutional-evaluation criteria (which include such items as system costs), would have to be traceable to other documents. The institutional-evaluation criteria trace to ICAO ANC-11 recommendations and other ICAO documentation rather than to the COCR. These criteria and their traceability are also presented in this report.

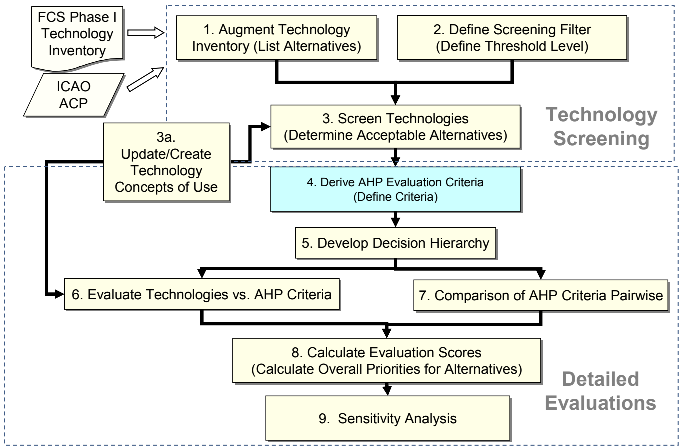


Figure 4–1.—FCS Technology Evaluation AHP—Step 4.

An initial review of the COCR resulted in the following observations. The COCR presents the expected operational environment, operating concept and required services for aeronautical communications. It was clear that a structured analysis of this material would result in the required functions of a future communications system. The COCR also includes material addressing (1) operational safety/security and performance requirements and (2) expected communications loading (required capacity in bits per second). It was equally clear that this material dictates the required performance of a future communications system. Hence, the initial review of the COCR resulted in the following important observation: the technical-evaluation criteria should consist of both functional and performance criteria.

The structured analysis of the COCR converted the operational concepts presented in the COCR to an operational context diagram. The operational context diagram was used to show the actors identified in the operational concepts, the interfaces between the actors and the system, and the required information flow across these interfaces. From the operational context diagram, structured analysis was used to identify the required functions of a future communications system. These required functions define the functional elements of the technical-evaluation criteria. As the required communications performance is explicitly specified in the COCR, the performance elements of the technical-evaluation criteria were obtained by inspection of the COCR.

The institutional-evaluation criteria were derived from ICAO ANC-11 Recommendations and the ICAO Global Plan for CNS/ATM Systems (ICAO Doc 9750).

A total of 21 technical technology evaluation criteria and 9 institutional technology evaluation criteria were defined. A summary of these criteria and traceability to source documents is provided in table 4–1. These technology-evaluation criteria were presented to the ICAO Aeronautical Communication Panel in May 2006. No substantive comments were received. Additional detail on the evaluation criteria development methodology and a full traceability of criteria to the COCR and ICAO consensus documents are provided in appendix C.

TABLE 4–1.—SUMMARY OF TECHNOLOGY EVALUATION CRITERIA

	Evaluation Criterion	**Description (and Sub-Items such as Capacity (C) and Performance (P))**		**Traceability**
1	Meets ATS Data Link Needs	**A. A/G & G/A Addressed** – Airport, TMA, En Route, Oceanic/Remote, Polar, Autonomous Zone	***C1***: Data Rate	1. Functions traced to COCR Operational Services (see traceability matrix in table C–5 for verification of needed and complete attributes); 2. Capacity metrics trace to COCR Section 6 3. Need for Priority Levels
			C2: Number of Users	
			P1: Priority Levels/QoS	
			P2: Latency	
		B. G/A Broadcast – Airport, TMA, En Route, Oceanic/Remote, Polar,	***C1***: Data Rate	
			C2: Number of Users	
			P1: Priority Levels/QoS	

	Evaluation Criterion	Description (and Sub-Items such as Capacity (C) and Performance (P))		Traceability
		Autonomous Zone	***P2:*** Latency	traces to COCR Section 5 4. Latency metrics trace to COCR Section 5
		C. A/A Addressed – Airport, TMA, En Route/Autonomous, Oceanic/Remote, Polar	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency	
2	Meets AOC Data Link Needs	**A. AOC Data –** Airport**,** TMA, En Route/Autonomous, Oceanic/Remote/Polar	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency	1. Functions traced to COCR Operational Services (see traceability matrix in table C–5 for verification of needed and complete attributes); 2. Capacity metrics trace to COCR Section 6 3. Need for Priority Levels traces to COCR Section 5 4. Latency metrics trace to COCR Section 5
3	Technical Readiness Level	Provides an indication of the technical maturity of the proposed technology (Technical Readiness Level)		11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 2
4	Standardization Status	Indicates the relevance and maturity of a proposed technology's standardization status.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 3
5	Certifiability	Provides a relative measure of the candidate complexity.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 3
6	Ground Infrastructure Cost	Estimates cost to service provider to provide coverage to a geographically large sector.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 4
7	Cost to Aircraft	Estimates relative cost to upgrade avionics with new technology.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 4
8	Spectrum Protection	Gauges the likelihood of obtaining the proper allocation of the target spectrum.		Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)
9	Security – A&I	Assesses whether authentication and data integrity are provided		COCR Security Requirements (table 4–11) Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)

	Evaluation Criterion	Description (and Sub-Items such as Capacity (C) and Performance (P))	Traceability
10	Security – Robustness to Jamming	Assesses technology resistance to jamming.	COCR Security Requirements (table 4–11)
11	Transition	Assesses acceptable transition characteristics, including: • Return on partial investment • Ease of technical migration (spectral, physical) • Ease of operational migration (air and ground users)	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-7)

4.2 Organize Criteria Into Decision Factors (AHP step 5)

After definition of evaluation criteria, the next step in the AHP was to build a decision factor hierarchy utilizing the derived criteria. This step, shown in the context of the full AHP, is shown in figure 4–2.

As indicated in section 2.3, the decision hierarchy provides a means of structuring individual decision factors into meaningful groups for which the relative importance of the factors can be assessed both within a group as well as across groups. Each group of decision factors makes up a branch of the decision factor hierarchy, where the group name as well as the individual group components are called decision factors or critical to quality factors (CTQs) for the decision. The resulting hierarchical structure includes what are called "global" decision factors or CTQ factors at the level 1 branch of the hierarchy.

For this application of the AHP, each derived evaluation criterion was considered an individual decision factor. To structure the criterion in hierarchical fashion, the technical evaluation criteria were considered separately from the institutional criteria (since there are similar characteristics of criteria within these two groups).

One way of identifying all candidate technical criteria was to itemize the components of a technical criterion. Each criterion includes the identification of the applicable COCR services, either ATS services, AOC services or both. Each also includes the identification of how communication connectivity is provided, specifically, ground/air (G/A) (and subsequently air/ground) addressed, ground-to-air (G-A) Broadcast, or air/air (A/A) addressed. These and other components that comprise technical evaluation criteria are shown in figure 4–3.

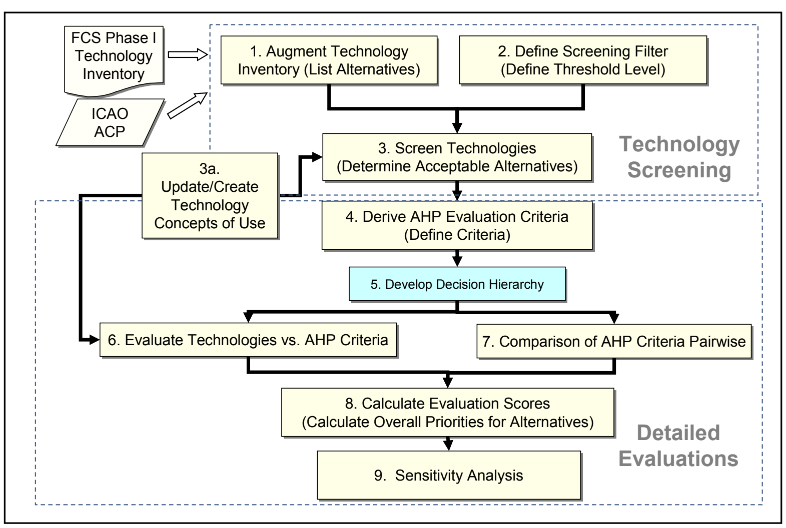


Figure 4–2.—FCS Technology Evaluation AHP—Step 5.

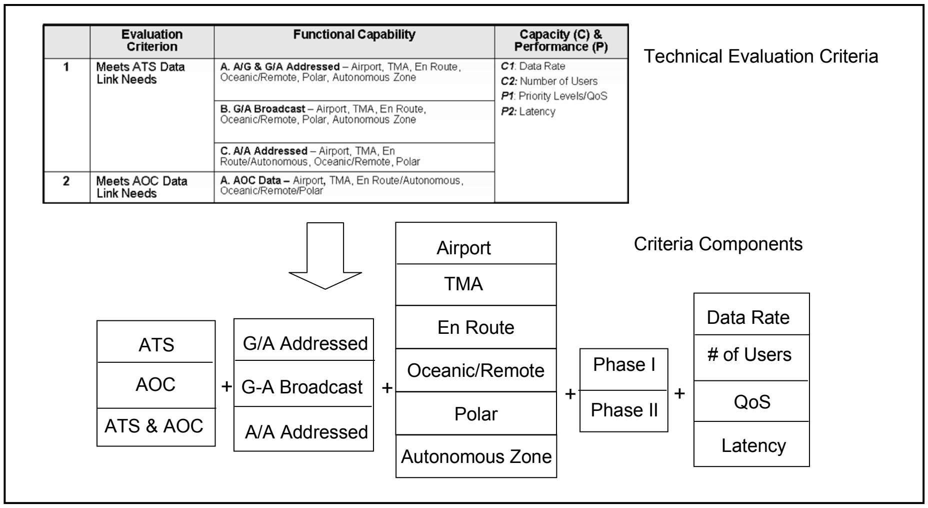


Figure 4–3.—Components of Technical Evaluation Criteria.

Various permutations of the components in figure 4–3 can be used to define specific technical evaluation criteria decision factors (e.g., meets ATS G/A addressed functionality in the airport domain while meeting COCR Phase 1 data rate requirements). Inspection of these technical evaluation criteria components in the context of the current study leads to several observations:

- As indicated in the FCS roadmap, implementation of a new technology in support of the FCS is in the 2020 and beyond timeframe; therefore, a focus on COCR Phase 2 requirements is warranted (note also that COCR Phase 2 requirements are more stringent than COCR Phase 1).
- Provisioning of an AOC-only service is not the focus of the FCS.
- Flight domains do not provide a meaningful discriminator among technologies:
  - Technologies that can meet oceanic/remote/polar domain requirements are limited to satellite and over horizon technologies; as it is understood based on the pre-screening analysis results that no technology provides the "silver bullet" across all domains, there is no need to bias results in considering these domains.
  - Technologies with limited communication range that provide high data rates have been nominated as candidates for the airport surface; this airport-only solution is not the scope of the FRS.
  - Finally, the domain-specific distinctions above can be made outside of the full technology comparison/evaluation; the focus is on technologies that can provide services across all flight domains (with an emphasis on continental domains).
- Performance requirements are inter-related; for example, specified data rate requirements are for a specified required number of users providing a defined QoS and meeting latency requirements; these requirements can be combined into a single "performance" component.

As a result of the observations noted above, the components that comprise technical evaluation criteria decision factors can be condensed. This is shown in figure 4–4.

Exploring all permutations of the remaining technical evaluation criteria components results in a set of six technical criteria decision factors. These six factors can be considered a "rollup" of individual technical criteria into a global decision factor. A hierarchy which identifies the six global level technical criteria decision factors and one level of decomposition (to show traceability to individual technical criteria) is shown in figure 4–5.

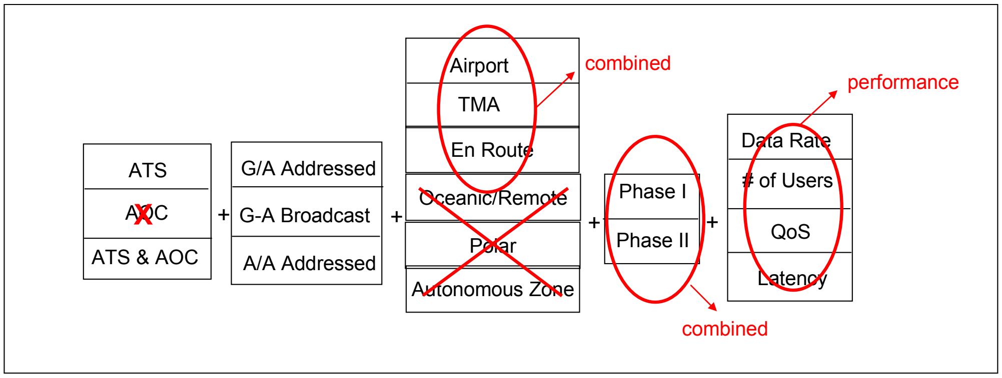


Figure 4–4.—Focusing Technical Evaluation Criteria
Components for Creating Decision Factors.

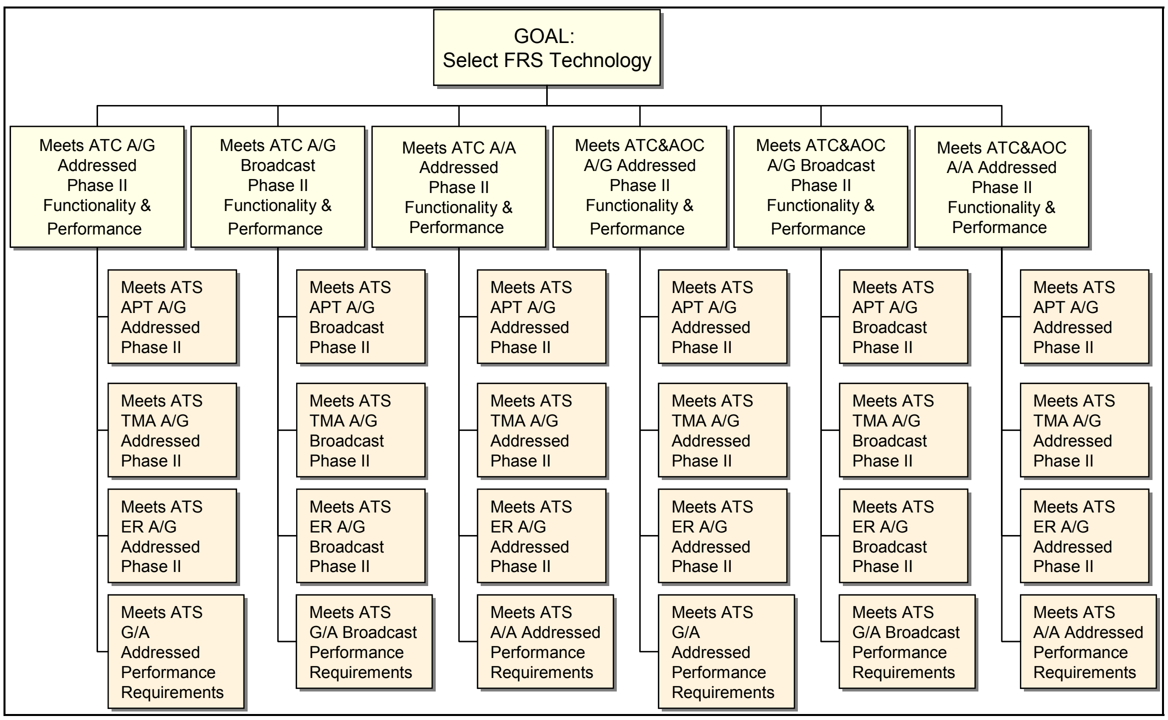


Figure 4–5.—Decision Hierarchy for Technical Evaluation Criteria.

The decision hierarchy elements addressing institutional criteria were defined based on inspection of institutional criteria and the grouping of these criteria into categories that address similar considerations of a communication system implementation. Specifically, the nine institutional criteria were organized along five major global decision factor lines including:

- Maturity for the aeronautical environment
- Ground cost
- Avionics equipage cost
- Safety and security
- Transition

A hierarchy that identifies these five global level institutional criteria decision factors and one level of decomposition (to show traceability to individual institutional criterion) is shown in figure 4–6.

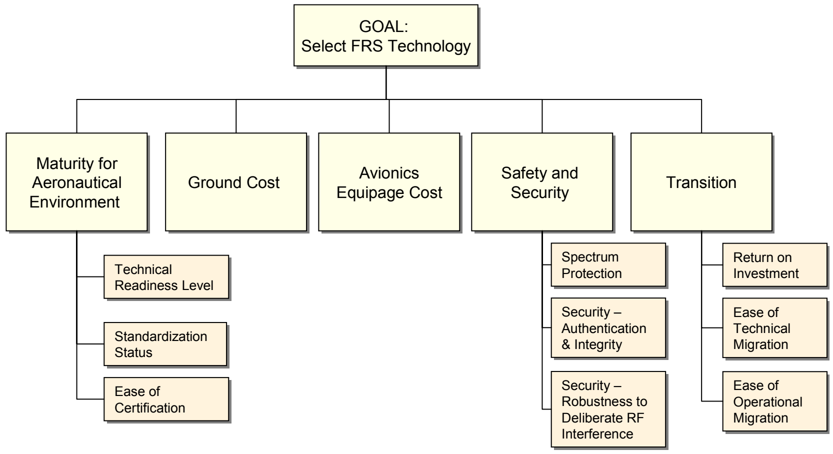


Figure 4–6.—Decision Hierarchy for Institutional Evaluation Criteria.

The full set of the global decision factors, or CTQs, defined for the technology evaluation analysis is summarized in table 4–2.

TABLE 4–2.—SUMMARY OF GLOBAL DECISION FACTORS

	Global Decision Factors/CTQs
1	Meets ATS G/A Addressed COCR Requirements
2	Meets ATS G-A Broadcast COCR Requirements
3	Meets ATS A/A Addressed COCR Requirements
4	Meets ATS & AOC G/A Addressed COCR Requirements
5	Meets ATS & AOC G-A Broadcast COCR Requirements
6	Meets ATS & AOC A/A Addressed COCR Requirements
7	Provides a highly mature technical solution
8	Provides a low ground infrastructure cost solution
9	Provides a low avionics installation cost solution
10	Provides a highly secure/safe solution
11	Provides low-risk/low complexity service provider transition

4.3 Evaluate Technologies (AHP step 6)

The next step in the AHP is the evaluation of technologies. As shown in figure 4–7, this is step 6 in the AHP.

Step 6 is addressed in two stages. First, technologies are evaluated against individual technical and institutional evaluation criteria (see section 4.3.1); next, based on the "rollup" of evaluation criteria to global decision factors, an assessment of a technology's ability to meet global decision factors is made (see section 4.3.2).

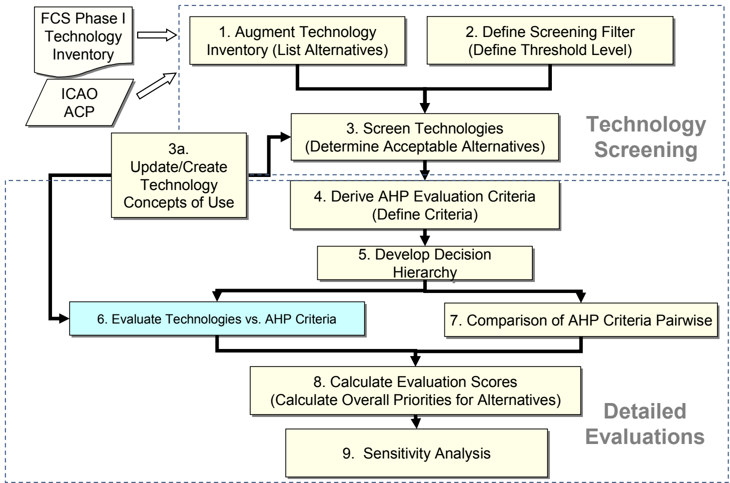


Figure 4–7.—FCS Technology Evaluation AHP—Step 6.

4.3.1 Evaluate Technologies Versus Evaluation Criteria

To perform the first stage of the technology evaluations, the technology concept of use material was used to build a matrix of key technology parameters. This included the identification of applicable flight domains; identification of provisioned communication functionality, performance capability, and evaluation of technology performance against institutional criteria. To support this activity, two sub-tasks were performed:

- Definition of evaluation criteria metrics
- Detailed technology investigation

Definition of metrics corresponding to technical functional criteria was straightforward. If a technology provided a functional capability, then it was judged to meet the functional criteria. For performance technical criteria, two parameters, provisioned data rate and number of users supported for a technology, were compared to specified requirements in the COCR. If the provisioned values were greater than or equal to the associated COCR requirement, the technology was considered to meet the performance criterion; otherwise the technology was considered to not meet the criterion. For latency and QoS, a qualitative assessment was made of a technology's ability to meet the most stringent COCR Phase 2 latency requirements of COCR and to provide QoS prioritization capability. For both of these parameters, technology performance capability was assessed. Finally, for institutional evaluation criteria, the metrics defined in the 2004 initial technology pre-screening task were used to make a red/yellow/green assessment. A summary of the COCR performance requirements used to assess technologies along with institutional criteria metrics from the 2004 pre-screening report (and utilized in this study) are provided in appendix D.

A summary of key technology parameters supporting the assessment of technologies is shown in table 4–3. Each technology that has been brought forward from the technology screening process is captured in a column of the table. The rows of the table correspond to technical and institutional evaluation criteria. Values in the table have been developed based on the technology description and defined concept of use for the aeronautical environment.

TABLE 4–3.—SUMMARY OF TECHNOLOGY PARAMETERS FOR APPLICATION IN THE FCS

Technology Family	**Cellular**	**PSR**	**Satellite**	**Satellite**	**Custom Broadband**				**Military**	**IEEE 802**
	WCDMA	P34	INMARSAT	Custom Satellite System (e.g. SDLS)	E-TDMA	LDL	B-VHF	UAT	LINK-16	IEEE 802.16e
Flight Domain										
APT	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TMA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
ENR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
OR	No	No	Yes	Yes	No	No	No	Yes	No	No
P	No	No	No	No	No	No	No	Yes	No	No
AOA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Functionality										
A/G & G/A Addressed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Ground Originated Broadcast	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
A/A Addressed	No	Yes	No	No	Yes	No	Yes	No	Yes	Yes
Air Originated Broadcast	No	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes
Data Rate (kbps)										
Data Rate for ATS (kbps)	960	173	32	30	100	100	421.2	3.712	115	13800
Data Rate for ATS+AOC (kbps)	960	173	32	30	100	100	421.2	3.712	115	13800
Max Number Users	552	512	2445	2500	512	512	1000	1000	64	1000
Max Number of Users (ATS-only for area-based a	N/A	N/A	5085	2500	N/A	N/A	N/A	N/A	N/A	N/A
QoS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Latency	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Average Coverage Area Volume (per area) (nm^3)	N/A	N/A	1335235		N/A	N/A	N/A	N/A	N/A	N/A
Technical solution maturity	0	1	1	1	0	1	0	1	0	0
Technical Readiness Level	2	1	2	1	0	1	0	2	2	2
Standardization Status	1	1	1	1	0	1	0	2	0	1
Certifiability	0	1	1	1	2	2	1	2	1	0
Ground infrastructure cost solution	0	1	1	0	1	1	1	1	0	2
Avionics installation cost	2	2	1	2	2	2	2	2	0	2
Security	1	1	1	1	1	1	1	1	1	1
Spectrum Protection	1	1	2	2	1	1	2	1	1	1
Security - Authentication and Integrity	2	2	2	2	1	1	2	1	2	2
Security - Robustness to Deliberate Interference	1	1	1	1	1	1	1	1	2	1
Transition	1	2	2	0	2	2	2	2	0	2

The technical criteria values from table 4–3 were compared against COCR requirements (as described above) and a meet/doesn't meet decision was made. Results of the evaluation of technologies against technical functional criteria are shown in table 4–4. In this table, if a technology provided a defined capability, a meets decision was made (shown by a check mark in the table).

TABLE 4–4.—ASSESSMENT OF TECHNOLOGIES AGAINST TECHNICAL FUNCTIONAL EVALUATION CRITERIA

	Function/Service		
	Air/Ground Addressed Data	Air/Air Addressed Data	Ground/Air Broadcast Data
W-CDMA	√		√
APCO P34	√	√	√
Inmarsat SBB	√		√
L-Band E-TDMA	√	√	√
Custom Satellite System (e.g. SDLS)	√		√
LDL	√		√
B-VHF	√	√	√
Link 16	√	√	√

Results of the evaluation of technologies against technical performance criteria are shown in table 4–5. In this table, if a technology met or exceeded COCR Phase 2 performance requirements, a meets decision was made (shown by a check mark).

TABLE 4–5.—ASSESSMENT OF TECHNOLOGIES AGAINST TECHNICAL PERFORMANCE EVALUATION CRITERIA

	Performance			
	Number of Users	Data Rate		QoS
		ATS-only	ATS & AOC	
W-CDMA	Meets in All Domains	√	√	√
APCO P34	Meets in All Domains	√	√	√
Inmarsat SBB	Meets for ATS Traffic Load[1]	√[2]	√[2]	√
Broadband E-TDMA	Meets in All Domains	√		√
Custom Satellite System (e.g. SDLS)	Meets in All Domains	√	√	√
LDL	Meets in TMA and ER Does not meet in APT	√		√
B-VHF	Meets in TMA and ER Does not meet in APT	√	√	√
Link 16	Meets in All Domains	√		√

1. Number of users supported calculated based on requirement that capacity be provided with availability of .99999 or greater; To meet required availability of capacity, an insufficient number of users can be supported when considering combined ATS & AOC traffic load
2. Meets per-user data rate requirements within each domain

Finally, results of the evaluation of technologies against institutional criteria are shown in table 4–6. As noted above, the red/yellow/green rating corresponds to the application of the institutional criteria metrics documented in appendix D.

TABLE 4–6.—ASSESSMENT OF TECHNOLOGIES AGAINST INSTITUTIONAL EVALUATION CRITERIA

	Technical Maturity	Ground Cost	Aircraft Cost	Safety/Security	Transition
W-CDMA	Red	Red	Green	Yellow	Yellow
APCO P34	Yellow	Yellow	Green	Yellow	Green
Inmarsat SBB	Yellow	Yellow	Yellow	Yellow	Green
Broadband E-TDMA	Red	Yellow	Green	Yellow	Green
Custom Satellite System (e.g. SDLS)	Yellow	Red	Green	Yellow	Red
LDL	Yellow	Yellow	Green	Yellow	Green
B-VHF	Red	Yellow	Green	Yellow	Green
Link 16	Red	Red	Red	Yellow	Red

4.3.2 Technology Performance Against Global Decision Factors

After the evaluation of technologies against individual evaluation criterion (i.e., individual decision factors), the next stage of AHP step 6 was the assessment of technologies against global decision factors or CTQs. The global factors are a “rollup” of individual decision factors. Thus, all individual evaluation criterion/decision factor assessments can be combined to make a global decision factor assessment as follows:

- If a technology meets all individual evaluation criterion/decision factors that comprise a global decision factor, then it “meets” the global decision factor; if one or more of the component individual evaluation criterion/decision factors is not met, then it doesn’t meet the global decision factor.
- For global decision factors addressing institutional criteria, if all component individual evaluation criterion/decision factors are scored green or yellow, a technology meets the global decision factor; if one or more of the component individual criterion/decision factors is scored red, then it doesn’t meet the global decision factor.

The full two-stage process where a summary of technology capabilities is used first to make an assessment against individual evaluation criterion and subsequently an evaluation against global decision factors that rollup individual criterion in hierarchical fashion is shown in figure 4–8.

Note in figure 4–8 that the first stage of the AHP step 6 evaluation was the use of technology capability information (shown on the upper left table on the figure) to make a meets/doesn’t meet assessment for an individual evaluation criterion. This meets/doesn’t meet assessment is shown visually using a binary scoring matrix (shown on the middle right portion of the figure, where 1 = meets and 0 = doesn’t meet). The results of the individual criterion assessment were then combined per the defined decision hierarchy (from AHP step 5) to make an assessment of technologies against global (i.e., Level 1) decision factors (shown on the lower left portion of the figure).

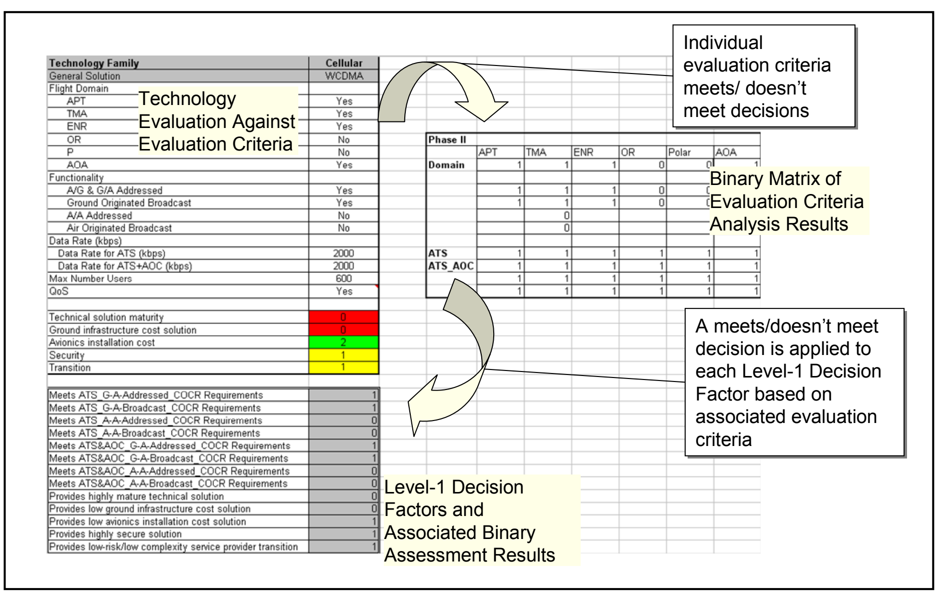


Figure 4–8.—Two-Stage Process for Evaluating Technologies Against Global Decision Factors.

4.4 Weight Decision Factors (AHP Step 7)

The next step in the AHP, a step that can occur in parallel with technology evaluation against global decision factors, was the assignment of weights to the decision factors. This step, AHP step 7, shown in the context of the complete AHP is provided in figure 4–9.

The weighting of decision factors is a key step in the AHP for incorporating stakeholder feedback. Decision factors are derived from evaluation criteria reflecting specified requirements for the FRS and ICAO recommendations for viable communication solutions. The perceived relative importance of these factors can vary widely among the FRS stakeholders. As an example, the relative importance of these factors as seen by an air navigation service provider likely differs from the relative importance of these factors as seen by an air carrier or other user organization.

In this study, a small group survey was conducted to achieve a preliminary response reflective of the air navigation service provider perspective. This survey and subsequent processing of survey responses was conducted as a means of gaining insight and confidence in the AHP steps that incorporate stakeholder feedback. The resulting weights for decision factors were then applied to the next steps of the AHP (technology scoring and sensitivity analysis), but as noted above, the associated results can only be considered preliminary. A complete and comprehensive application of AHP step 7 is planned for the final component of the FCS technology evaluation, 2006 to 2007.

A wide variety of survey styles are possible for gaining stakeholder feedback on global decision factors (i.e., CTQs). While each survey style utilizes a pair-wise comparison between all global decision factors, a major discriminator is the granularity of the comparison scale used for the pair-wise comparison. The simplest scale would include a possible assessment of decision factors being more important, less important or equal to each other. On the other end of the spectrum, the most complex scale identified in literature was a 20-point scale where the relative importance comparison between two decision factors ranged from –10 to 10, where –10 indicated the first decision factor was "extremely less important" than the second, 0 indicated the factors were of equal importance, and 10 indicated the first decision factor was "extremely more important" than the second.

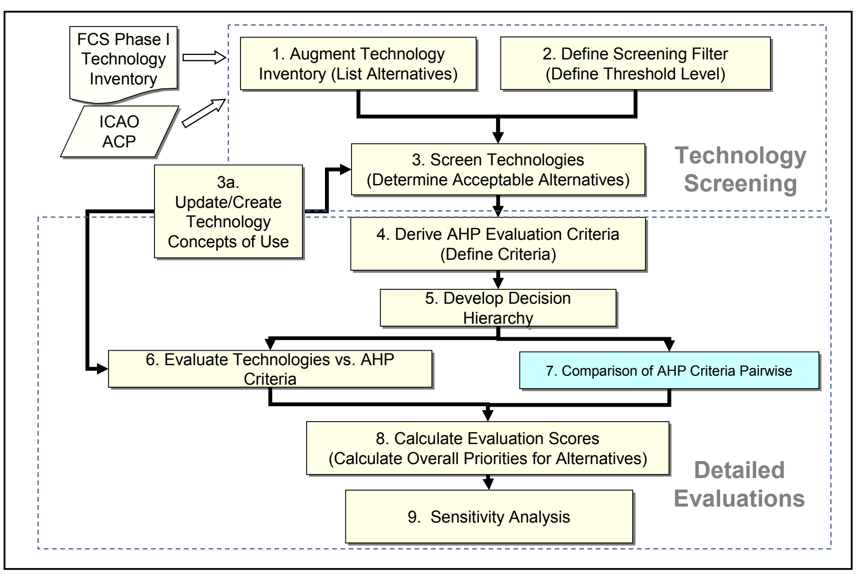


Figure 4–9.—FCS Technology Evaluation AHP—Step 7.

For this task, a nine-point scale was used in the survey conducted in this study. As introduced in section 2.3, the scale rates one decision factor to a second factor in one of the following ways:

- Extremely more important than: 9
- Very strongly more important than: 7
- Strongly more important than: 5
- Moderately more important than: 3
- Equally important to: 1
- Moderately less important than: 1/3
- Strongly less important than: 1/5
- Very strongly less important than: 1/7
- Extremely less important than: 1/9

Note that associated with each comparison value noted above is a numeric score. These scores are used later in the process to assign a numeric relative importance weight to each decision factor. As there were 11 global decision factors or CTQs in the defined decision hierarchy for technology evaluation (see section 4.2), there were 55 pair-wise comparison questions in the preliminary survey generated to collect stakeholder feedback on the relative importance of the decision factors. An excerpt of this survey is shown in figure 4–10.

The collected survey responses were used to populate decision matrices, where quantitative values associated with survey responses were captured. To synthesize survey results across all respondents, a geometric mean was computed for each comparison question. The resulting decision matrix for the averaged pair-wise comparison of decision factors is shown in figure 4–11.

Using this matrix, matrix mathematics was applied to calculate the matrix eigenvalues. The largest eigenvalue was used to find the associated eigenvector for the matrix. The normalized eignenvector values are the resulting relative importance weights associated with each CTQ or global decision factor. The preliminary average weighted results are shown in figure 4–12.

Pair-Wise Comparison of CTQ Metrics

ID	CTQ Metric A		Relative Magnitude	Relationship Sense	CTQ Metric B
1	Meets ATS_G-A-Broadcast_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
2	Meets ATS_A-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
3	Meets ATS&AOC_G-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
4	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
5	Meets ATS&AOC_A-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements

Figure 4–10.—Excerpt from Preliminary Stakeholder Survey of Decision Factor Importance.

Scale:

1 - equally important	1/3 - moderately less important
3 - moderate more important	1/5 - strongly less important
5 - strongly more important	1/7 - very strongly less important
7 - very strongly more important	1/9 - extremely less important
9 - extremely more important	

Is [row] more important than [column]? (>1)	Meets ATS_G-A-Addressed_COCR Requirements	Meets ATS_G-A-Broadcast_COCR Requirements	Meets ATS_A-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	Meets ATS&AOC_A-A-Addressed_COCR Requirements	Provides highly mature technical solution	Provides low ground infrastructure cost solution	Provides low avionics installation cost solution	Provides highly secure/safe solution	Provides low-risk/low complexity service provider transition
Meets ATS_G-A-Addressed_COCR Requirements		3.3227	5.245	1	3.936	5.711	1	0.725	0.762	0.903	1.476
Meets ATS_G-A-Broadcast_COCR Requirements	0.301		0.903	0.238	2.29	0.859	0.582	0.654	0.394	0.437	0.689
Meets ATS_A-A-Addressed_COCR Requirements	0.1907	1.1076		0.369	1.108	3	0.517	0.763	0.415	0.301	1.312
Meets ATS&AOC_G-A-Addressed_COCR Requirements	1	4.2103	2.713		3	4.584	1.38	1.552	0.844	0.903	1.552
Meets ATS&AOC_G-A-Broadcast_COCR Requirements	0.254	0.4366	0.903	0.333		2.141	1.07	1.016	0.491	0.582	1
Meets ATS&AOC_A-A-Addressed_COCR Requirements	0.1751	1.1647	0.333	0.218	0.467		0.242	0.229	0.191	0.204	0.492
Provides highly mature technical solution	1	1.7188	1.933	0.725	0.935	4.139		0.803	0.394	0.394	0.422
Provides low ground infrastructure cost solution	1.3797	1.5281	1.31	0.644	0.985	4.36	1.246		0.339	0.316	0.644
Provides low avionics installation cost solution	1.3121	2.5365	2.408	1.185	2.036	5.245	2.537	2.954		0.451	2.036
Provides highly secure/safe solution	1.1076	2.2902	3.323	1.108	1.719	4.904	2.537	3.16	2.217		2.537
Provides low-risk/low complexity service provider transition	0.6776	1.4509	0.762	0.644	1	2.033	2.371	1.552	0.491	0.394	

Figure 4–11.—Preliminary Decision Matrix.

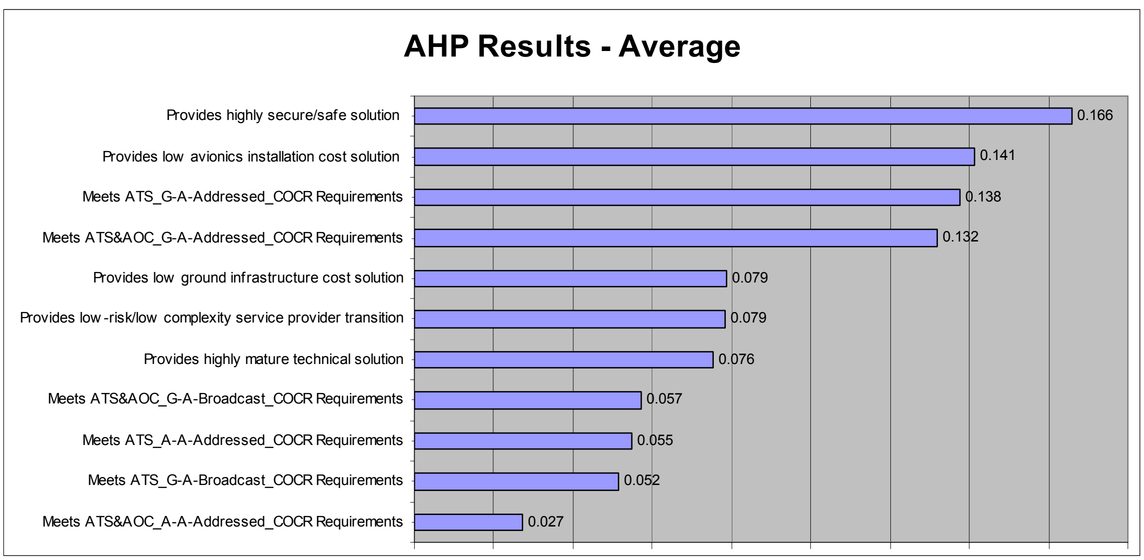


Figure 4–12.—Preliminary Averaged Weighting of Global Decision Factors (i.e., CTQs).

In figure 4–12, the most important decision factors for FRS technology evaluation (from the preliminary survey) were found to include the provision of a secure and safe solution; having low-cost avionics implementations; and meeting ground-to-air addressed functionality and performance communication requirements.

Is [row] more important than [column]? (>1)	Meets ATS_G-A-Addressed_COCR Requirements	Meets ATS_G-A-Broadcast_COCR Requirements	Meets ATS_A-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	Meets ATS&AOC_A-A-Addressed_COCR Requirements
Meets ATS_G-A-Addressed_COCR Requirements		3.3227	5.245	1	3.936	5.711
Meets ATS_G-A-Broadcast_COCR Requirements	0.301		0.903	0.238	2.29	0.859
Meets ATS_A-A-Addressed_COCR Requirements	0.1907	1.1076		0.369	1.108	3
Meets ATS&AOC_G-A-Addressed_COCR Requirements	1	4.2103	2.713		3	4.584
Meets ATS&AOC_G-A-Broadcast_COCR Requirements	0.254	0.4366	0.903	0.333		2.141
Meets ATS&AOC_A-A-Addressed_COCR Requirements	0.1751	1.1647	0.333	0.218	0.467	

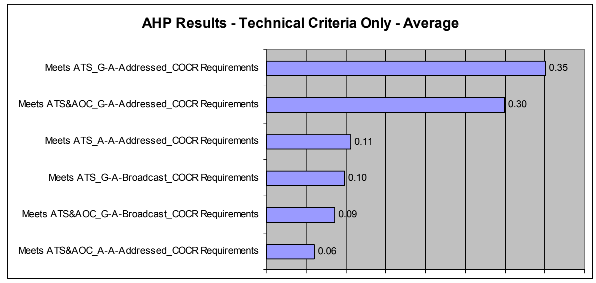


Figure 4–13.—Preliminary Decision Matrix and Weights for Technical Decision Factors.

Is [row] more important than [column]? (>1)	Meets ATS_G-A-Addressed_COCR Requirements	Meets ATS_G-A-Broadcast_COCR Requirements	Meets ATS_A-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Addressed_COCR Requirements	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	Meets ATS&AOC_A-A-Addressed_COCR Requirements	Provides highly mature technical solution	Provides low ground infrastructure cost solution	Provides low avionics installation cost solution	Provides highly secure/safe solution	Provides low-risk/low complexity service provider transition
Meets ATS_G-A-Addressed_COCR Requirements							1	0.725	0.762	0.903	1.476
Meets ATS_G-A-Broadcast_COCR Requirements							0.582	0.654	0.394	0.437	0.689
Meets ATS_A-A-Addressed_COCR Requirements							0.517	0.763	0.415	0.301	1.312
Meets ATS&AOC_G-A-Addressed_COCR Requirements							1.38	1.552	0.844	0.903	1.552
Meets ATS&AOC_G-A-Broadcast_COCR Requirements							1.07	1.016	0.491	0.582	1
Meets ATS&AOC_A-A-Addressed_COCR Requirements							0.242	0.229	0.191	0.204	0.492
Provides highly mature technical solution	1	1.7188	1.933	0.725	0.935	4.139		0.803	0.394	0.394	0.422
Provides low ground infrastructure cost solution	1.3797	1.5281	1.31	0.644	0.985	4.36	1.246		0.339	0.316	0.644
Provides low avionics installation cost solution	1.3121	2.5365	2.408	1.185	2.036	5.245	2.537	2.954		0.451	2.036
Provides highly secure/safe solution	1.1076	2.2902	3.323	1.108	1.719	4.904	2.537	3.16	2.217		2.537
Provides low-risk/low complexity service provider transition	0.6776	1.4509	0.762	0.644	1	2.033	2.371	1.552	0.491	0.394	

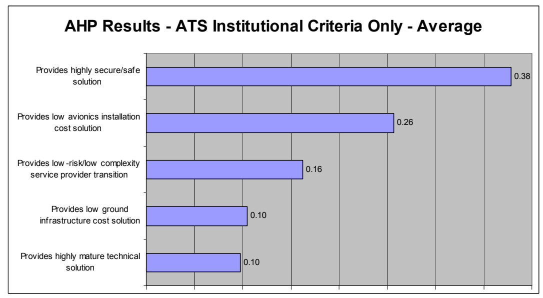


Figure 4–14.—Preliminary Decision Matrix and Weights for Institutional Decision Factors.

In support of the sensitivity analysis, two additional decision factor weighting structures were computed. The first weighting structure consisted of the resulting weights when considering only technical decision factors. The associated decision matrix and resulting weights for this scenario are shown in figure 4–13.

When considering only those decision factors or CTQs that relate to technical evaluation criteria, meeting G/A addressed functional and performance requirements are clearly the most important factors in this preliminary survey. The second set of results supporting sensitivity analysis was the resulting decision factor weights when considering only those decision factors that relate to institutional evaluation criteria. The associated decision matrix and resulting weights for this scenario are shown in figure 4–14.

When considering only those decision factors or CTQs that relate to institutional evaluation criteria, providing a highly safe/secure solution and low avionics implementation cost are clearly the most important factors in this representative survey.

4.5 Compute Preliminary Technology Scores (AHP Steps 8 and 9)

The final two steps of the AHP included the calculation of evaluation scores and sensitivity analysis, as shown in figure 4–15.

The work performed to implement an initial iteration of these steps is documented below.

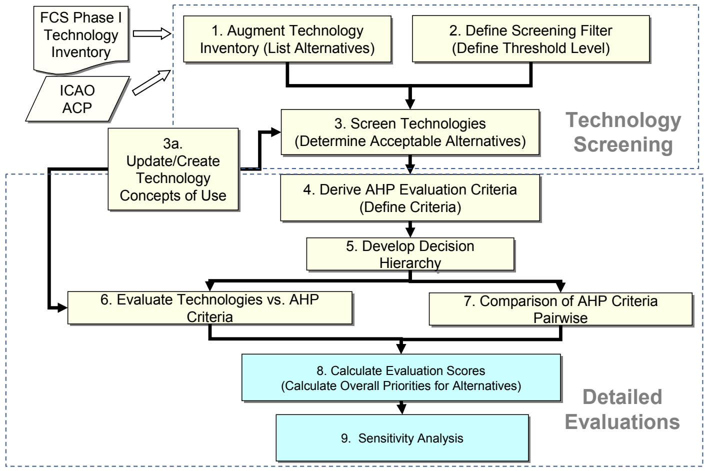


Figure 4–15.—FCS Technology Evaluation AHP—Steps 8 and 9.

4.5.1 Calculate Evaluation Scores

Technology scores were calculated by combining technology assessments against the global decision factors (CTQs) with calculated decision factor weights. For each decision factor met by a technology, the weight assigned to the factor was added to the cumulative score for the technology. An example scoring table is shown in table 4–7.

In table 4–7, the far left column identifies the global decision factors (CTQs). The next column identifies whether for a specific technology (W-CDMA in this case) the CTQ is met by the technology based on the assessment of AHP step 6. The second column from the right identifies the weight associated with each CTQ based on the calculations of AHP step 7. Finally, the far right column includes the score components as well as the total score for the technology.

TABLE 4–7.—CALCULATING TECHNOLOGY SCORES

Technology under Evaluation:	WCDMA		
Selected Ranking Perspective:	Average		
Technology CTQ Assessment			
Global Decision Factor/CTQ	**Meets**	CTQ Weight	**SCORE**
Meets ATS_G-A-Addressed_COCR Requirements	☑	13.75%	0.1375
Meets ATS_G-A-Broadcast_COCR Requirements	☑	5.16%	0.0516
Meets ATS_A-A-Addressed_COCR Requirements	☐	5.47%	
Meets ATS&AOC_G-A-Addressed_COCR Requirements	☑	13.19%	0.1319
Meets ATS&AOC_G-A-Broadcast_COCR Requirements	☑	5.72%	0.0572
Meets ATS&AOC_A-A-Addressed_COCR Requirements	☐	2.73%	
Provides highly mature technical solution	☐	7.55%	
Provides low ground infrastructure cost solution	☐	7.87%	
Provides low avionics installation cost solution	☑	14.12%	0.1412
Provides highly secure/safe solution	☑	16.59%	0.1659
Provides low-risk/low complexity service provider transitior	☑	7.85%	0.0785
	☑	**TOTAL**	**0.7638**

	All Criteria
W-CDMA	.7638
APCO P34	1
Inmarsat SBB	.7289
Custom Satellite System (e.g. SDLS)	.7608
E-TDMA	.7354
LDL	.7289
B-VHF	.9245
Link 16	.2479

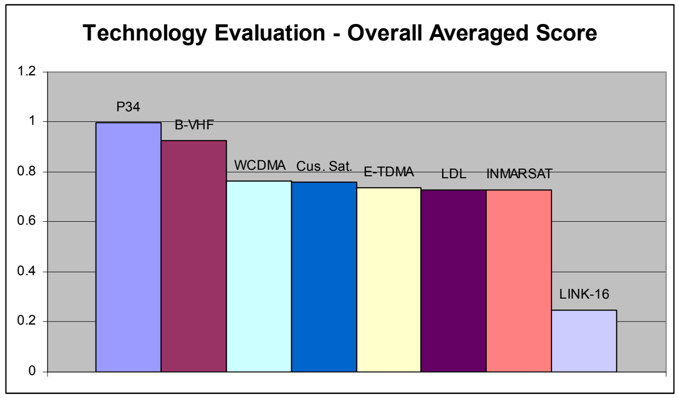


Figure 4–16.—Preliminary Technology Evaluation Results—Overall Average Score.

The scoring table was used to calculate preliminary technology scores based on the global decision factors (CTQs) defined in AHP step 5; the technology evaluations against the decision factors in AHP step 6; and the preliminary stakeholder survey used to develop CTQ weights in AHP step 7. The resulting preliminary set of results for screened technologies is shown in figure 4–16.

In the preliminary results, P34 and B-VHF (at L-Band) are the best performers while one technology, Link 16, is a noticeably poor performer.

4.5.2 Sensitivity Analysis

To further explore technology performance, a sensitivity analysis was performed to identify the best technology performers when considering technical evaluation factors and institutional evaluation factors individually. When considering only technical decision factors (CTQs), the preliminary decision weights calculated in figure 4–13 were used. Applying these weights and considering technology performance based only on technical decision factors; the preliminary results shown in figure 4–17 were calculated.

The results shown in figure 4–17 can be used as a positive discriminator of technologies. In other words, technologies that can meet all or a majority of the technical evaluation criteria and hence FRS requirements can be identified. In the preliminary set of results, five technologies including P34, B-VHF (at L-Band), W-CDMA, Custom Satellite, and L-Band E-TDMA meet or come close to meeting all technical criteria. Other technologies appear to not perform well in this category; however, further inspection of evaluation results indicates that when considering only ATS service requirements and subsequent evaluation criteria (as compared to ATS and AOC service requirements), all technologies except Link 16 perform well against the technical criteria.

When considering only institutional decision factors (CTQs), the preliminary decision weights calculated in figure 4–14 were used. Applying these weights and considering technology performance based only on institutional decision factors; the preliminary results shown in figure 4–18 were calculated.

The results shown in figure 4–18 can be used as a negative discriminator. That is, technologies that do not perform well against criteria that are indicative of factors associated with a viable solution (e.g., cost and risk) can be identified. In the preliminary results, the noticeably poor performer in this regard is Link 16.

	Technical Criteria Only
W-CDMA	.8345
APCO P34	1
Inmarsat SBB	.4495
Custom Satellite System (e.g. SDLS)	.8345
E-TDMA	.6151
LDL	.4495
B-VHF	1
Link 16	.1656

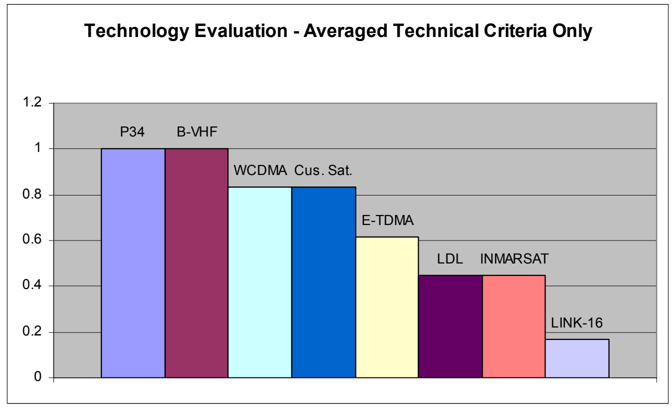


Figure 4–17.—Preliminary Technology Evaluation Results—Technical Criteria Average Score.

	Institution al Criteria Only
W-CDMA	.7974
APCO P34	1
Inmarsat SBB	1
Custom Satellite System (e.g. SDLS)	.7327
E-TDMA	.9023
LDL	1
B-VHF	.9023
Link 16	.3783

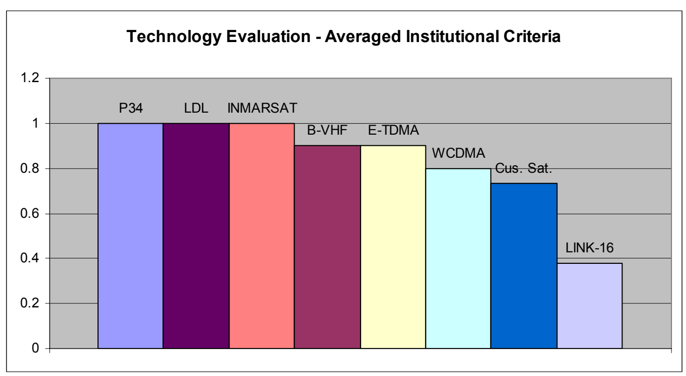


Figure 4–18.—Prelimnary Technology Evaluation Results—Institutional Criteria Average Score.

In summary, an evaluation of preliminary technology scores indicates that Link 16 may not be an overall strong performer. Further investigation of the factors that led to the poor score indicated that its score would not be significantly changed through additional iteration of the AHP. This is due to the technology's poor performance with regard to cost, the required operating mode to meet COCR requirement (and associated capacity and user limitations), and immature standardization status. As a result, it is obvious at this juncture that this technology will not be a best performer of the screened technologies.

An additional result is that LDL and Inmarsat SBB may not be strong performers in meeting combined ATS and AOC technical requirements (although LDL is still under definition); but these technologies may be satisfactory for an ATS-only system.

4.6 Applying Detailed Technology Investigation Results

The preliminary set of results calculated in section 4.5.1 indicates that the strongest technology performers (in terms of technical and institutional decision factors) appear to be P34 and B-VHF (at L-Band). A second group of capable technologies includes W-CDMA, Custom Satellite, L-Band E-TDMA, LDL, and Inmarsat SBB.

Of the best performers noted above, the following have undergone detailed analysis:

- Inmarsat SBB/Satellite solutions
- P34
- LDL
- 802.16

The results of these detailed studies are described in appendix E. An overview of the study results is provided below.

Detailed technology evaluations of satellite communication systems (with a focus on provision of required availability) indicated that Inmarsat SBB will not meet availability requirements. A custom satellite solution designed to meet COCR availability requirements will, in fact, require a highly redundant and costly architecture. This result aligns with the results of other similar studies.[131] For this reason, the satellite solutions are not considered viable solutions for the continental domain. This does not preclude; however, their effective role in providing communication capability in remote and oceanic airspace.

Detailed analysis of the L-Band propagation environment, and P34 and LDL performance in a derived representative L-Band air-ground model provided valuable insight into the performance of these technologies. Specifically, it was found that the L-Band channel model, in some instances, can be considered quite severe with regard to fading. Considering a mountainous terrain, a mean root-mean-square-delay spread (RMS-DS) was calculated to be on the order of 1.4 μs. In terms of a technology such as P34 (an OFDM system with a per carrier symbol rate of 4.8 kbps); this channel can be considered a flat fading channel. For a technology such as LDL (with a more simplistic modulation scheme, binary continuous phase frequency shift keying (CPFSK), and a data rate of 62.5 kbps), the channel can be much more severe and is a borderline frequency-selective fading channel case, which can result in irreducible BERs and requires more costly mitigation techniques such as adaptive equalization.

Detailed analysis of P34 and LDL also considered the interference potential of these technologies on existing radio-navigation technologies currently operating in the L-Band. The work indicated that the performance of LDL is slightly better than that of P34 in that P34 acts more of an interference source than LDL to both Mode S and UAT receivers. Modeling results indicate that a carrier to interference (C/I) ratio of 12 to 15 dB is required for minimum degradation of the UAS receiver and 15 dB or better is required to not substantially degrade the Mode S preamble detection behavior, although Mode S interference measurements are recommended to fully understand the interference potential. The results of the P34 and LDL detailed analyses indicate that these technologies are still both viable candidates; however, further exploration of the channel model and receiver implementations is warranted for validating LDL performance in this environment; and interference measurements for these technologies against Mode S and DME receivers are recommended.

A detailed analysis examined the performance of 802.16e in the anticipated propagation environment for the C-Band aeronautical channel. Using a channel model adapted from a detailed airport surface area model developed by Ohio University, the performance of 802.16e was found to be quite good for most of the movement area (incorporating equalization techniques). While this technology has good potential applicability for this domain, additional analysis to look at additional technology features to enhance performance (e.g., HARQ, fast feedback channel and diversity sub-carrier permutations) is warranted.

Other capable technology performers identified in the technology screening and detailed evaluations that require further detailed evaluation include B-VHF (at L-Band), E-TDMA, and W-CDMA. These are candidate technologies for the detailed evaluation in the final component of the FCS technology investigation task (2006 to 2007).

5. RESULTS, RECOMMENDATIONS, AND NEXT STEPS

5.1 Results

Considering a candidate pool of 47 technologies and applying the adapted AHP to perform a technology screening, a set of 8 candidate FRS solutions for continental airspace (i.e., airport, terminal, and en route flight domains) were identified. These included:

- W-CDMA
- P34
- LDL
- B-VHF (at L-Band)
- L-Band E-TDMA
- Inmarsat SBB
- Custom Satellite Solution
- Link 16

These results were refined through detailed analysis of a subset of the technologies above and initial implementation of the detailed evaluation components of the AHP (i.e., steps 4 to 9). The initial detailed evaluation results are summarized in figure 5–1.

Figure 5–1 shows the proposal to remove several screened technology candidates from further consideration as a general FRS solution. This includes Link 16 and the satellite solutions. Link-16 was removed as a result of poor technology performance against screening criteria (and subsequent low scoring in the initial detailed evaluation). The satellite solutions were removed from further consideration as a result of detailed analysis of these technologies that focused on availability performance.

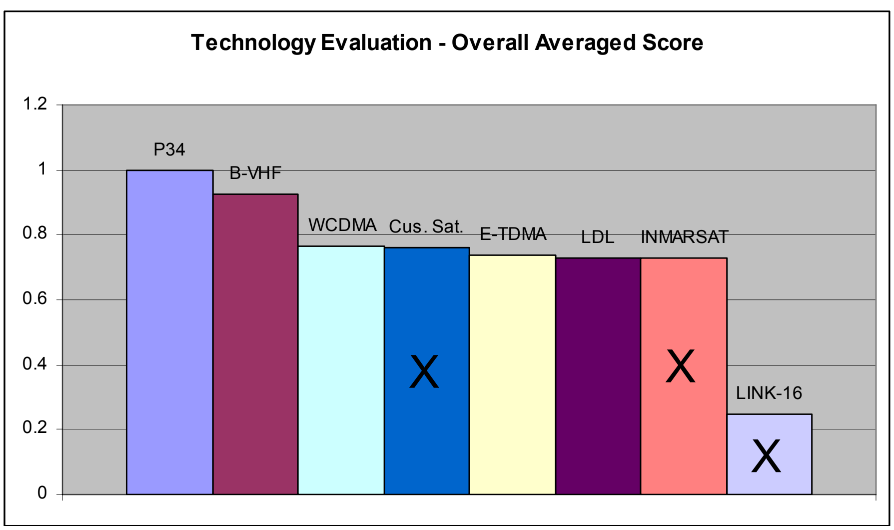


Figure 5–1.—Initial Detailed Evaluation Results.

The strongest performing technologies in the initial detailed evaluation have also undergone in-depth technical analysis. For these technologies, P34 and LDL, the selected focus of the comprehensive evaluation was threefold including protocol performance, bit error rate (BER) performance in the estimated L-Band propagation environment and interference potential to operational L-Band systems (e.g., Mode S, UAT, and DME). Detailed analysis results indicate that these candidates have strong potential for the FRS, but additional channel performance (particularly for LDL) and interference investigations are warranted.

In the final phase of the FCS, it is recommended that in-depth analysis also be conducted for the other technologies performing strongly in the initial detailed analysis. These include W-CDMA, L-Band E-TDMA, and B-VHF (at L-Band).

As a point of reference, the initial evaluation results have been contrasted to the findings of the 2004 FCS technology pre-screening task. It should be noted; however, that the pre-screening task had a slightly different focus as compared to the current technology screening study. Specifically, in the pre-screening task, consideration was given to both voice and data communication requirements. The focus of the current study is on data-only requirements. In the pre-screening, results and sensitivity analysis were used to identify best all-around technology performers as well as the best performers with regard to data communications. These best performers from the pre-screening included B-VHF (with a recommendation for implementation in L-Band with appropriate physical layer changes); W-CDMA; P34; and VDL3 (with a recommendation for a new physical layer and band-shifting to L-Band). A visual comparison of FCS technology pre-screening and technology screening results is shown in figure 5–2.

Figure 5–2 indicates that all of the recommendations resulting from the pre-screening task are again best performers in the technology screening task. One additional candidate, L-Band E-TDMA, is also identified as a candidate technology of interest in the current study.

In addition to the technologies noted above as general aeronautical communication candidates for continental airspace, technology recommendations specific to the airport and oceanic domains have been captured. Specifically, 802.16e is recognized as a technology with the best potential applicability for the airport surface and terminal domains. Inmarsat SBB, Iridium services, and any emerging satellite technologies that utilize AMS(R)S spectrum are recommended technologies for remote airspace where terrestrial infrastructure either does not exist or cannot be implemented.

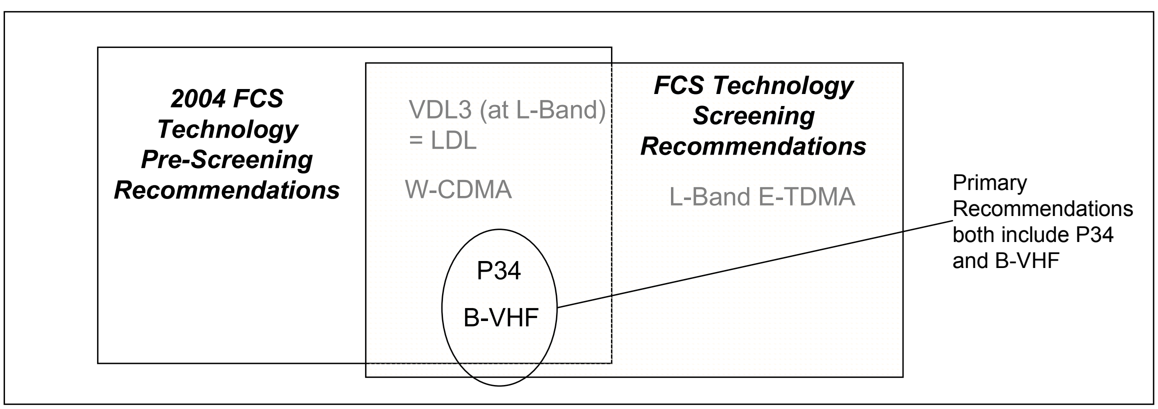


Figure 5–2.—Comparison of Study Results to 2004 Pre-Screening Recommendations.

5.2 Recommendations and Next Steps

Based on a refined screening process that was responsive to feedback received on the initial FCS technology screening, a set of eight candidate technologies have been identified for consideration for the FCS. It is recommended that these eight technologies (W-CDMA, P34, LDL, B-VHF (at L-Band), L-Band E-TDMA, Inmarsat SBB, Custom Satellite Solution, and L-16) constitute a technology short-list for consideration for the FRS.

A process for detailed evaluation of these technologies based on industry-standard decision-making methodologies was defined and a successful initial iteration of the evaluation process performed. It is recommended that a thorough and final iteration of the detailed evaluation process be performed in the final phase of the FCS.

In this study, a set of five candidate technologies were identified as leading contenders for applicability to the FRS. A subset of these candidates has undergone detailed analysis. It is recommended that detailed analysis of the remaining leading candidates, namely W-CDMA, L-Band E-TDMA, and B-VHF (at L-Band) be considered for the final phase of the FCS.

Based on implementation of the recommendations noted above, the final phase of the FCS technology evaluation will complete detailed technical analysis of candidate technologies for the FRS. It is anticipated that outputs of the final phase of technology evaluation will be the recommendation of a technology that meets COCR-specified FRS requirements, is a viable candidate for implementation, and would be ready to enter the aeronautical data-link standardization process.

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APPENDIX B. CONCEPTS OF USE FOR NEW TECHNOLOGY CANDIDATES

This appendix provides a description and concept of use for FRS candidate technologies that have been newly added to the technology inventory including:

- L-Band Data Link (LDL)
- L-Band E-TDMA
- Custom Satellite Solution

Material specific to these technologies are provided in the following subsection.

B.1 LDL Concept of Use

The LDL technology candidate is essentially the VDL Mode 3 (VDL3) technology specification band-shifted and with a re-designed physical layer for L-Band operation. This technology is classified as part of the custom broadband technology family. This family includes a range of broadband technology specifications with potential applicability to aeronautical communications. A subset of these technologies, including LDL, is being specifically designed for aviation.

While the proposed VDL3 technology was considered for implementation in a manner similar to the current aeronautical radio architecture (e.g., a host of radio of radios throughout the NAS providing sector-based coverage), the proposed concept for LDL is the implementation of a regular grid of radio sites. Figure B–1 shows how NAS wide coverage above 18,000 ft could be obtained using (such) a regular grid.

While the upper-layer protocols of the proposed LDL technology are almost identical to VDL3, the physical layer has been re-defined to accommodate operations in L-Band. A summary of the proposed parameters (and a comparison to VDL3 parameter values) is provided in figure B–2.

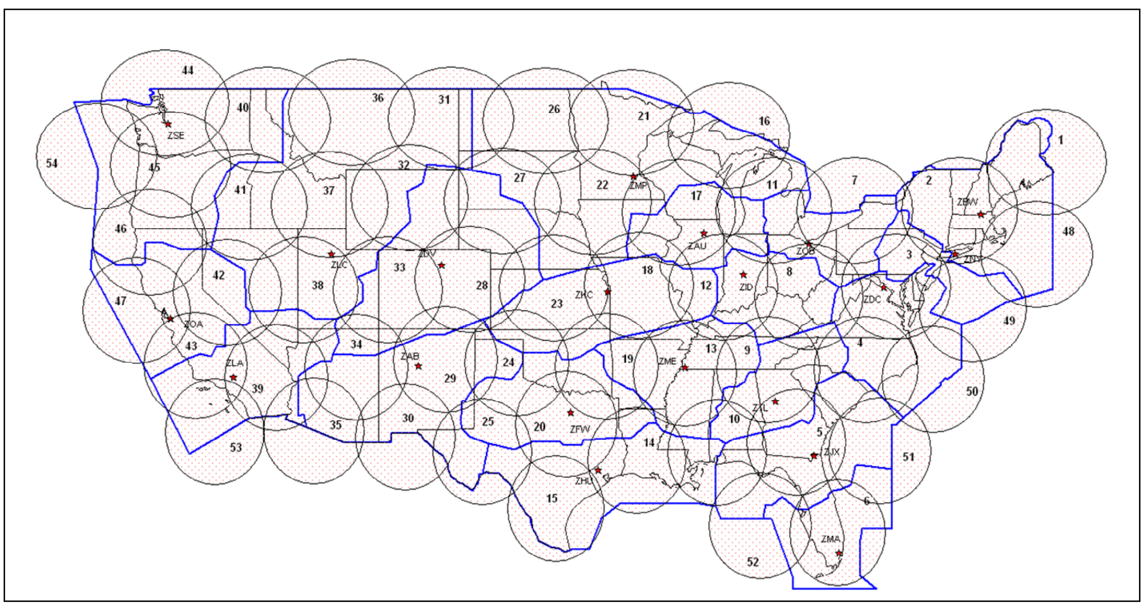


Figure B–1.—Sample Regular Grid Implementation of LDL Ground Stations.

	VDL Mode 3	LDL
Frequency Band	118 -137 MHz	960 – 1024 MHz
Modulation Type	D8PSK	Binary CPFSK
Bit Rate	31.5 kbps	62.5 kbps *
Eb/No (including losses)	17 dB	11 dB **
Cochannel D/U	20 dB	6 - 9 dB

* To be optimized. Can be anywhere between 37.5 kbps to 100 kbps.
** Noncoherent detection. Could be improved with more complex demodulator

Figure B–2.—Overview of LDL Physical Layer Parameters.

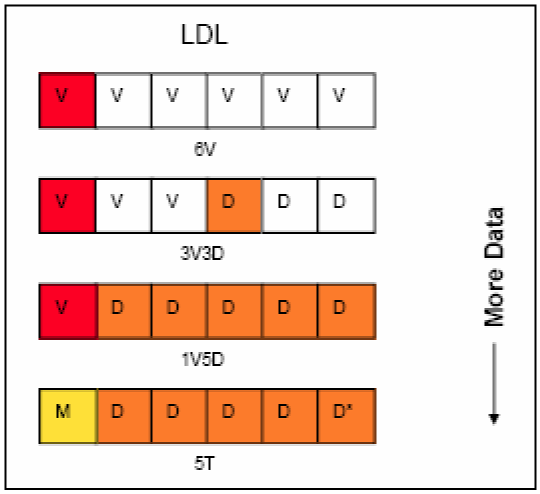


Figure B–3.—Overview of LDL Operational Modes.

The LDL proposal accommodates a range of voice and data communication services. These are offered using a five-slot TDMA frame structure, where each frame is 120 ms in duration. The selected application mode of LDL for FRS data communications is the 5T configuration. This configuration is compared and contrasted with other configurations in figure B–3.

In figure B–3, the M represents a management time slot used to accommodate management traffic while V/D time slots accommodate voice or data, accordingly. Channel access requests for LDL 5T are random access requests processed as part of the management traffic (similar to VDL3 3T mode). Although the technology protocol is still under definition, initial estimates of data capacity values range from 37.5 to 100 kbps.

B.2 L-Band E-TDMA Concept of Use

Similar to the definition of LDL above, the L-Band E-TDMA technology concept is the defined E-TDMA technology band shifted to L-Band and with appropriate physical layer adaptations. Like LDL, this technology is a custom broadband concept specifically designed for aviation.

The original E-TDMA concept was developed by SOFREAVIA at a time when VDL3 and VDL4 were envisioned to be inadequate in providing a general purpose data link for aeronautical applications. It is based on a cellular architecture of ground station, where global ground coordination is not required. Design drivers for the technology have not been physical layer performance, but rather managing of Quality of Service (QoS) throughout service volumes.

The E-TDMA concept was defined to implement a statistical self-synchronization TDMA frame structure; this concept is assumed to be maintained in the L-Band implementation. A representative depiction of the frame structure is provided in figure B–4.

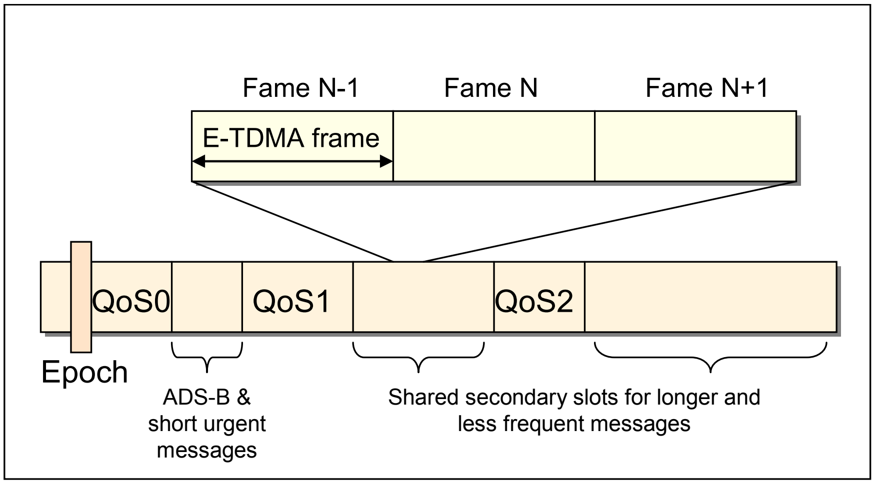


Figure B–4.—Representative L-Band E-TDMA Frame Structure.

The frame structure shown above includes unconditional access for every mobile in an exclusive primary slot in every frame. Mobiles additionally can utilize reservation-based access to pools of secondary slots with each frame.

As noted above, focus of the design of this technology has not been on physical layer protocols. Candidate physical layer protocols are yet to be defined. Thus, in the current analysis, range and capacity values for this candidate have been assumed based on similar technology candidates in the custom broadband technology family.

B.3 Custom Satellite Solution Concept of Use

This technology concept is a general definition that addresses satellite payloads or architectures that are specifically designed for aviation. Some specific examples of related specification and implementation projects include:

- Satellite Data-Link System: A European Space Agency Initiative that defines a bent-pipe geostationary satellite architecture implementing CDMA at L-Band for aeronautical applications; design goals include low-cost infrastructure and low operating costs
- Multi-function Transport Satellite (MTSAT): Japan's operational primary/backup geostationary satellite architecture providing aeronautical services; current applications include GPS augmentation

As this technology is rather general, no specific concept of use is defined. Rather, it is envisioned that the concept of use would be developed to fully support emerging aeronautical operational concepts, services, and associated radio system requirements. As a basis for analysis in this study, specific architecture features and performance values defined for SDLS have been utilized. An overview of the proposed SDLS functional architecture is shown in figure B–5.

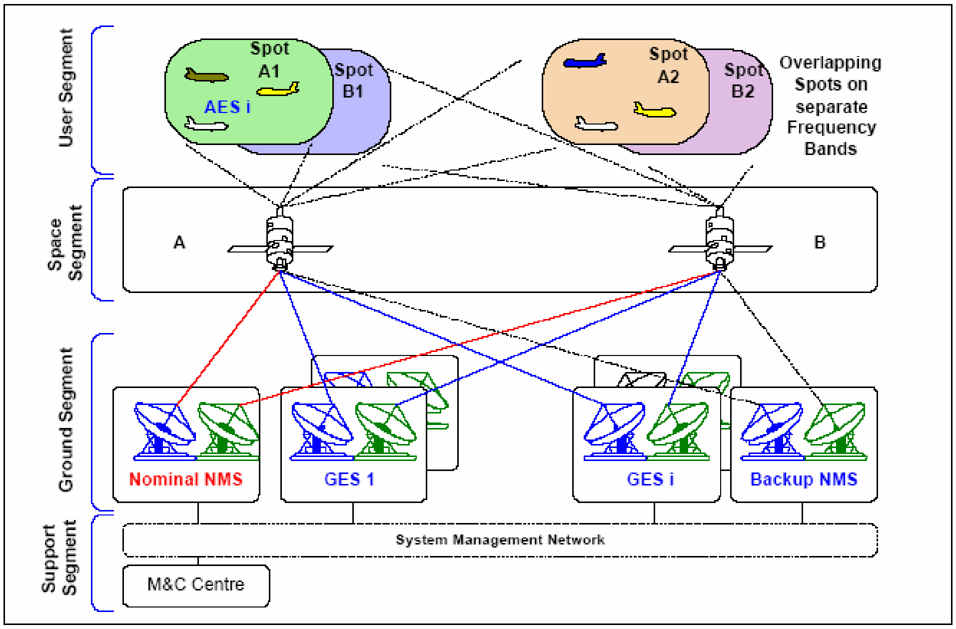


Figure B–5.—SDLS Functional Architecture.

Although not finalized, this concept includes two geostationary satellites providing overlapping coverage to mobile users. The ground segment includes Network Master Stations, Ground Earth Stations, and network routing equipment.

To support different user communications, SDLS uses TDMA and CDMA. The CDMA is accomplished using gold codes with a spreading factor of 127. The TDMA structure depends on the particular channel (multiple channels are defined). The basic modulation is QPSK with rate ½ turbocoding specified. Additional concept of use information specific to SDLS can be found in the technology pre-screening report (sections 3.5.3.2).[132]

APPENDIX C. EVALUATION CRITERIA DEVELOPMENT, DETAILS AND TRACEABILITY

The material below describes the technology evaluation criteria development process and documents full traceability of the resulting criteria to the Concept of Operations and Communication Requirements (COCR) for the (FRS) and other consensus ICAO documentation.

C.1 Evaluation Criteria Development

A structured analysis of the COCR was undertaken to derive a set of evaluation criteria that would be directly traceable to the COCR. During the process of developing these criteria, it was discovered that this process would only yield what could be considered technical-evaluation criteria. An equally important set of criteria that address strategic objectives of a future aeronautical communication system, termed institutional evaluation criteria (which include such things as system costs), would have to be traceable to other documents. For this study the institutional evaluation criteria trace to ICAO ANC-11 recommendations and the ICAO Global Plan for CNS/ATM Systems (ICAO Doc 9750) rather than to the COCR. These criteria and their traceability are also presented in this paper.

An initial review of the COCR resulted in the following observations. The COCR presents the expected operational environment, operating concepts, and required services for aeronautical communications. It was clear that a structured analysis of this material would result in the required functions of a future communications system. The COCR also includes material addressing (1) operational safety/security and performance requirements and (2) expected communications loading (required capacity in bits per second). It was equally clear that this material dictates the required performance of a future communications system. Hence, the initial review of the COCR resulted in the following important observation: the technical-evaluation criteria should consist of both functional and performance criteria.

The structured analysis of the COCR converted the operational concepts presented in the COCR to an operational context diagram. The operational context diagram is used to show the actors identified in the operational concepts, the interfaces between the actors and the system, and the required information flow across these interfaces. From the operational context diagram, a structured analysis was used to identify the required functions of a future communications system. These required functions define the functional elements of the technical-evaluation criteria. Because the required communications performance is specified in the COCR, the performance elements of the technical-evaluation criteria were obtained by inspection of the COCR.

The institutional-evaluation criteria were derived from ICAO ANC-11 Recommendations and the ICAO Global Plan for CNS/ATM Systems (ICAO Doc 9750).

An illustration of the approach to derive functional and performance criteria is provided in figure C–1. The left-hand branch of figure C–1 illustrates the following process. The COCR identifies future operational concepts. The COCR further identifies the required operational services to implement these concepts. In the communications domain, the operational services have an associated required communication performance (RCP). The RCP requirements and associated COCR communication load requirements were used to derive technology evaluation performance requirements.

The right-hand branch of figure C–1 identifies the functional analysis process, accommodating stakeholder input that was used to derive functional capability requirements.

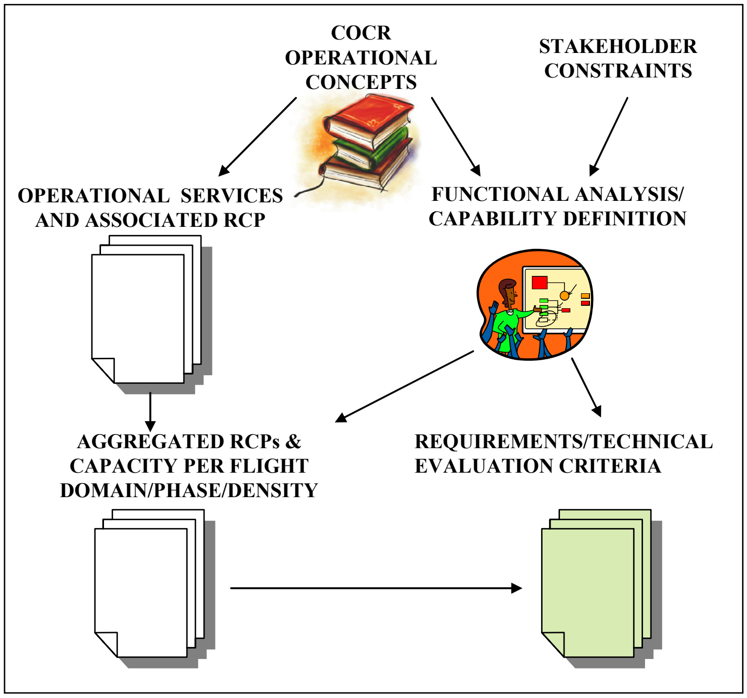


Figure C–1.—Deriving Functional and Performance Evaluation Criteria From COCR.

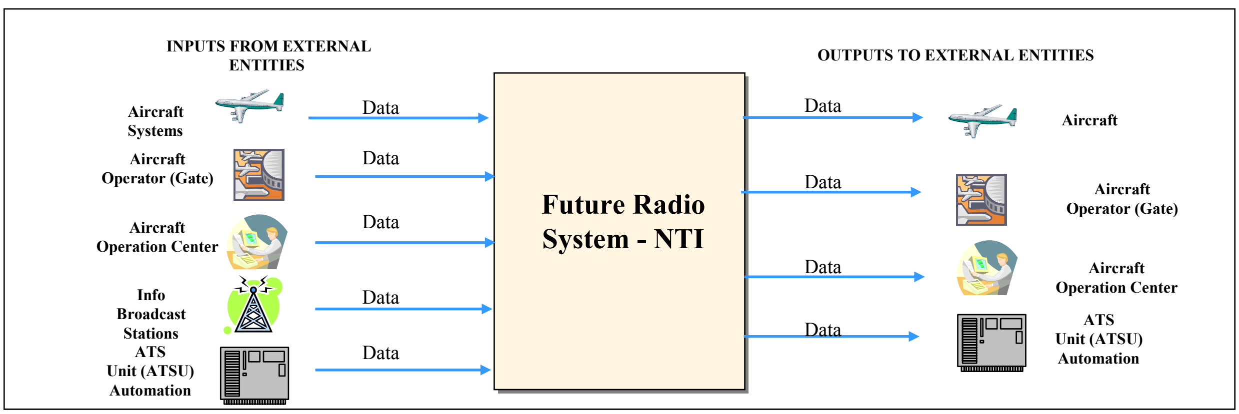


Figure C–2.—FRS-NTI Context Diagram.

The functional analysis of the COCR began with the definition of an FRS context diagram. This diagram identifies who uses the system (i.e., the system actors) and the system interfaces (i.e., the communication connections between the actors and the FRS). Both actors and interfaces for the FRS were identified by parsing the COCR. The resulting context diagram is provided in figure C–2.

The name “Future Radio System”—New Technology Implementation (FRS-NTI) is used in the figure above to reflect assumptions that were applied during the development of the context diagram. These include:

- Voice Communications are allocated to 25 kHz DSB-AM and 8.33 kHz DSB-AM systems per ATMAC recommendations and ICAO ACP WGW direction (not included in the context of FRS-NTI)
- Surveillance/ADS-B interfaces are allocated to legacy UAT and Mode S systems and are not included in this context of the FRS-NTI
- Navigation interfaces are accommodated by legacy/planned navigation systems

Application of these assumptions results in a context diagram that does not encompass the entire FRS concept, but instead provides a more focused set of capabilities that are of interest in this analysis. This focused capability is denoted FRS-NTI.

Through observation of the context diagram and review of service flows over the identified interfaces, key communication functions of the FRS-NTI were identified. These included functions such as provision of aircraft-to-ground communications in all flight domains, enabling both broadcast and addressed communications, and accommodating both ATS and AOC services. Inspection of the identified functions led to an abstraction of required functional characteristics that address *how* transactions are conducted (i.e., broadcast vs. addressed, and ground-to-air, air-to-ground, and air-to-air); *where* transactions are applicable (e.g., airport domain, Terminal Maneuvering Area (TMA), etc.); and *what* information is exchanged in the transactions (e.g., ATS services vs. AOC services).

Organizing the resulting functional characteristics led to the functional decomposition of the COCR shown in figure 3. Note that this picture includes a high-level decomposition of COCR voice functions. The COCR does include voice functions and requirements, but due to stakeholder inputs to focus on data requirements, voice requirements were not carried forth in the development of technology evaluation criteria. As shown in figure C–3, the future communications system must provide AOC and ATS communications functions. Although these may not be on the same system, both services will be required. These services must be provided across several operational domains, including Airport (APT), TMA, En Route (ENR), Oceanic/Remote/Polar (ORP), and Autonomous Operations Area (AOA). Services can be distinguished by their connectivity, that is, air-to-ground, ground-to-air, and air-to-air; as well as by their addressability, which has two main distinctions, addressed and broadcast. Analysis of the context diagram indicated that the air-to-ground and ground-to-air functions could be grouped without loss of discriminating detail.

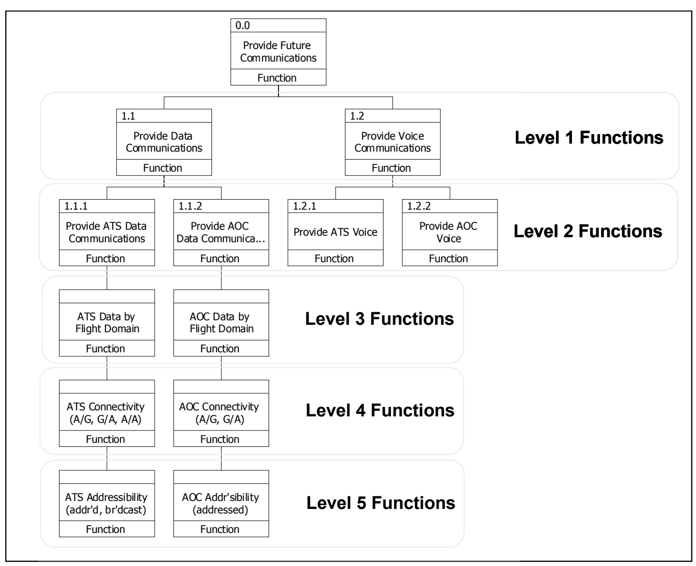


Figure C–3.—Functional Decomposition of (Derived) COCR Operational Context Diagram.

Table C–1 shows the suggested technical evaluation functional criteria associated with the data functions included in figure C–3.

TABLE C–1.—SUGGESTED TECHNICAL EVALUATION CRITERIA (FUNCTIONAL)

Suggested Criteria Level 1	Suggested Criteria Level 2	Applicable Domains
Meets ATS Data Link Needs	A/G & G/A Addressed	APT, TMA, ENR, ORP, AOA
	Ground Originated Broadcast	APT, TMA, ENR, ORP, AOA
	A/A Addressed	APT, TMA, AOA
	Air-Originated Broadcast	APT, TMA, ENR, ORP, AOA
Meets AOC Data Link Needs	A/G & G/A Addressed	APT, TMA, ENR, ORP

The functions defined above all trace to the operational services described in the COCR section 2.0. Functions have been verified to be complete and unique by capturing forwards and backwards traceability to the COCR. An excerpt from the traceability matrix is provided in table C–2.

TABLE C–2.—TRACEABILITY OF SUGGESTED TECHNOLOGY-EVALUATION FUNCTIONS TO COCR (EXCERPT)

	COCR ATM Service	ATS A/G & G/A Addressed Airport	ATS A/G & G/A Addressed TMA	ATS A/G & G/A Addressed EnRoute	ATS A/G & G/A Addressed Oceanic/Remote	ATS A/G & G/A Addressed Polar	ATS A/G & G/A Addressed Autonomous	ATS G/A Broadcast Airport	ATS G/A Broadcast TMA	ATS G/A Broadcast EnRoute	ATS G/A Broadcast Oceanic/Remote
ATS	**ATC** - Clearance (ACL)	X	X	X	X	X					
ATS	**ATC** - Mic Check (AMC)	X	X	X	X	X		X	X	X	X
ATS	**ATC** - DL Taxi Clearance (D-TAXI)	X									
ATS	**ATC** - Departure Clearance (DCL)	X									
ATS	**ATC** - Downstream Clearance (DCL)										
ATS	**ATC** - Pilot Preferences Downlink (PPD)	X	X	X	X	X					
ATS	**ATC** - Dynamic Route Availability (DYNAV)			X							
ATS	**ATC** - Arrival Manager Info (ARMAND)			X							
ATS	**ATC** - Common Traject. Coord. (COTRAC)		X	X	X	X	X				
ATS	**Auto Downlink** - FP Consist. (FLIPCY)	X	X								
ATS	**Auto Downlink** - FP Intent (FLIPINT)		X	X	X	X					
ATS	**Auto Downlink** - System Access Param (SAP)		X	X	X	X					

The technical evaluation performance criteria were derived from inspection of the COCR and include the required communications capacity, which was subdivided into required *Data Rate* and required *Number of Users*; the ability to provision *Quality of Service (QoS)*; and the ability to provide the required *Latency* performance. Analysis indicated that a technology must meet these performance requirements while provisioning the functions identified above, otherwise the technology was not truly capable of satisfying the needs of aviation. Traceability of the performance criteria to the COCR is provided in table C–3.

TABLE C–3.—TRACEABILITY OF SUGGESTED TECHNOLOGY-EVALUATION PERFORMANCE CRITERIA TO COCR

Criterion	COCR References
Data Rate	Table 6–19 A/G Capacity Requirements – Phase 1; Table 6–20 A/G Capacity Requirements – Phase 2; Table 6–21 A/G Capacity Requirements excluding A-EXEC service – Phase 2; Table 6–22 A/G Capacity Requirements for each Aircraft using a Separate 'Channel' – Phase 1; Table 6–23 A/G Capacity Requirements for each Aircraft using a Separate 'Channel' – Phase 2; Table 6–24 A/G Capacity Requirements for each Aircraft using a Separate 'Channel' excluding the A-EXEC service – Phase 2
Number of Users	Table 6–1 PIAC Projections
QoS Priority	Table 5–9 Data COS (Type DG – A/G Addressed); Table 5–10 Data COS (Type DA – A/A Addressed); Table 5–11 Data COS (Type DB – A/A Broadcast); Table 5–12 COS Assignments (Network Management) – Phase 1 & 2 Table 5–13 COS Assignments (ATS) – Phase 1 & 2; Table 5–14 COS Assignments (AOC) – Phase 1 & 2
Latency	Table 5–6 FRS Allocated Data Performance (ATS) - Phase 1; Table 5–7 FRS Allocated Data Performance (ATS) - Phase 2; Table 5–8 FRS Allocated Data Performance (AOC) - Phase 1 & 2;

The institutional evaluation criteria were essentially derived from Recommendation 7/5 from the 11th Air Navigation Conference, which reads

> *"Continue to monitor emerging communication systems technologies but undertake standardization work only when the systems meet all of the following conditions:*
> *1) meet current and emerging ICAO ATM requirements*
> *2) be technically proven and offer proven operational benefits*
> *3) be consistent with the requirements for safety*
> *4) be cost-beneficial*
> *5) be consistent with the global plan for CNS/ATM Systems"*

To further understand recommendation number 5, the global plan for CNS/ATM systems was reviewed. The global plan indicates in section 5.14 (Future Communication) Trends that the "most important question to be asked when considering a new system is whether it meets existing or emerging operational and user requirements. Other factors to be considered are standardization, certification, harmonious deployment by various users, and cost benefit considerations."

The Global Plan also includes a Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation (appendix A to chapter 2). This statement outlines requirements for implementation and operation of future CNS/ATM systems including the requirement for flexible transition; the ability to provide continuous service with specified integrity; and with required priority, security, and interference protection.

From the ANC-11 recommendations (and a review of the Global Plan) the proposed institutional evaluation criteria are shown in table C–4.

TABLE C–4.—SUGGESTED INSTITUTIONAL EVALUATION CRITERIA

Criteria	Reference
1) Technical Readiness Level	11th ICAO ANC (Sept/Oct 2003) Recommendation 7/5 – # 2
2) Standardization Status	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO ANC (Sept/Oct 2003) Recommendation 7/5 – #3
3) Certifiability	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO ANC (Sept/Oct 2003) Recommendation 7/5 – # 3
4) Cost – Ground Infrastructure	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO ANC (Sept/Oct 2003) Recommendation 7/5 – # 4
5) Cost - Aircraft	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO ANC (Sept/Oct 2003) Recommendation 7/5 – # 4
6) Spectrum Protection	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)
7) Security – A&I	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8); and COCR Security Requirements (Table 4–11, p68)
8) Security – Robustness to Jamming	COCR Security Requirements (table 4–11, p. 68)
9) Transition	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-7)

C.2 Complete Traceability of Evaluation Criteria

Traceability of evaluation criteria is organized into two components. The first is the detailed traceability of functional and performance technical criteria to the COCR. The second component is the full set of technology evaluation criteria with documented source traceability.

C.2.1 Traceability of Technical Evaluation Criteria

Functional evaluation criteria used for assessment of technologies for the FRS were derived through structured analysis of the COCR (described in section C.1). To ensure that a complete, necessary, and unique set of required functions (and associated functional criteria) were defined, traceability of derived functions to COCR services was performed. The resulting traceability matrix provides both forward-traceability (to ensure that each COCR service is accommodated by at least one defined communication function) and reverse-traceability (to ensure that every defined communication function is needed to accommodate at least one COCR service). An excerpt of this traceability matrix was provided in table 2 above. The full traceability table is provided in table C–5.

TABLE C–5.—TRACEABILITY OF TECHNICAL FUNCTIONAL CRITERIA

		COCR ATM Service	ATS A/G & G/A Addressed Airport	ATS A/G & G/A Addressed TMA	ATS A/G & G/A Addressed EnRoute	ATS A/G & G/A Addressed Oceanic/Remote
	ATS	**ATC** - Clearance (ACL)	X	X	X	X
	ATS	**ATC** - Mic Check (AMC)	X	X	X	X
	ATS	**ATC** - DL Taxi Clearance (D-TAXI)	X	X		
	ATS	**ATC** - Departure Clearance (DCL)	X			
	ATS	**ATC** - Downstream Clearance (DSC)			X	X
	ATS	**ATC** - Pilot Preferences Downlink (PPD)	X	X	X	X
	ATS	**ATC** - Dynamic Route Availability (DYNAV)			X	X
	ATS	**ATC** - Arrival Manager Info (ARMAND)			X	
	ATS	**ATC** - Common Traject. Coord. (COTRAC)	X	X	X	X
	ATS	**ATC** - Auto Execute (A-EXEC)			X	X
	ATS	**Auto Downlink** - FP Consist. (FLIPCY)	X	X	X	X
	ATS	**Auto Downlink** - FP Intent (FLIPINT)	X	X	X	X
	ATS	**Auto Downlink** - System Access Param (SAP)		X	X	
	ATS	**Flight Info** - Operational Terminal Info (D-OTIS)	X	X	X	
	ATS	**Flight Info** - RVR (D-RVR)	X	X	X	
	ATS	**Flight Info** - Operational Enroute Info (D-ORIS)			X	X
	ATS	**Flight Info** - Meterological Info (D-SIGMET)	X	X	X	X
	ATS	**Flight Info** - Automatic Terminal Info (D-ATIS)	X	X	X	
	ATS	**Flight Info** - Flight Updates (D-FLUP)	X			
	ATS	**Flight Info** - Surface Info (D-SIG)	X	X		
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -ATC Surveillance (SURV)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) - Enhanced Visual Acquisition (EVA)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Wake Broadcast (WAKE)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - In-Trail Procedures (ITP)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Crossing & Passing (C&P)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Sequencing & Merging (S&M)				
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Paired Approach (PAIRAPP)				
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Air-to-Air Self Separation (AIRSEP)				
	ATS	**Emergency** - Urgent Contact (URCO)	X	X	X	X
	ATS	**Emergency** - DL Alert (D-ALERT)	X	X	X	X
	ATS	**Comm Mngt** - Data Link Login (DLL)	X		X	X
	ATS	**Comm Mngt** - Comm Mngt (ACM)	X	X	X	X
	ATS	**Comm Mngt** - Net Connect	X		X	X
	ATS	**Comm Mngt** - Net Keep Alive	X	X	X	X
	AOC	AOC Login				
	AOC	Out Off On In (OOOI)				
	AOC	NOTAM Request/NOTAMs				
	AOC	Free Text				
	AOC	Wx Request/Wx Report				
	AOC	Position Report				
	AOC	Flight Status				
	AOC	Fuel Status				
	AOC	Gate/Connections Status				
	AOC	Engine Performance Reports				
	AOC	Maintence Troubleshooting				
	AOC	FP Request/FP Data				
	AOC	Load Sheet Request/Transfer				
	AOC	Flight Log Transfer				
	AOC	Real Time Maintenance Info				
	AOC	Graphical Wx Info				
	AOC	Real Time Wx Report				
	AOC	Technical Logbook Update				
	AOC	Cabin Log Book Transfer				
	AOC	Update Electronic Library				
	AOC	Software Loading				

TABLE C–5.—Continued.

		COCR ATM Service	ATS A/G & G/A Addressed Polar	ATS A/G & G/A Addressed Autonomous	ATS G/A Broadcast Airport	ATS G/A Broadcast TMA	ATS G/A Broadcast EnRoute
	ATS	**ATC** - Clearance (ACL)	X				
	ATS	**ATC** - Mic Check (AMC)	X		X	X	X
	ATS	**ATC** - DL Taxi Clearance (D-TAXI)					
	ATS	**ATC** - Departure Clearance (DCL)					
	ATS	**ATC** - Downstream Clearance (DSC)	X				
	ATS	**ATC** - Pilot Preferences Downlink (PPD)	X				
	ATS	**ATC** - Dynamic Route Availability (DYNAV)	X				
	ATS	**ATC** - Arrival Manager Info (ARMAND)					
	ATS	**ATC** - Common Traject. Coord. (COTRAC)	X	X			
	ATS	**ATC** - Auto Execute (A-EXEC)	X				
	ATS	**Auto Downlink** - FP Consist. (FLIPCY)	X				
	ATS	**Auto Downlink** - FP Intent (FLIPINT)	X				
	ATS	**Auto Downlink** - System Access Param (SAP)					
	ATS	**Flight Info** - Operational Terminal Info (D-OTIS)			X	X	X
	ATS	**Flight Info** - RVR (D-RVR)			X	X	X
	ATS	**Flight Info** - Operational Enroute Info (D-ORIS)	X				X
	ATS	**Flight Info** - Meterological Info (D-SIGMET)	X	X	X	X	X
	ATS	**Flight Info** - Automatic Terminal Info (D-ATIS)			X	X	X
	ATS	**Flight Info** - Flight Updates (D-FLUP)					
	ATS	**Flight Info** - Surface Info (D-SIG)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -ATC Surveillance (SURV)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) - Enhanced Visual Acquisition (EVA)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Wake Broadcast (WAKE)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - In-Trail Procedures (ITP)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Crossing & Passing (C&P)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Sequencing & Merging (S&M)					
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Paired Approach (PAIRAPP)					
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Air-to-Air Self Separation (AIRSEP)					
	ATS	**Emergency** - Urgent Contact (URCO)	X				
	ATS	**Emergency** - DL Alert (D-ALERT)	X				
	ATS	**Comm Mngt** - Data Link Login (DLL)	X				
	ATS	**Comm Mngt** - Comm Mngt (ACM)	X				
	ATS	**Comm Mngt** - Net Connect	X	X			
	ATS	**Comm Mngt** - Net Keep Alive	X	X			
	AOC	AOC Login					
	AOC	Out Off On In (OOOI)					
	AOC	NOTAM Request/NOTAMs					
	AOC	Free Text					
	AOC	Wx Request/Wx Report					
	AOC	Position Report					
	AOC	Flight Status					
	AOC	Fuel Status					
	AOC	Gate/Connections Status					
	AOC	Engine Performance Reports					
	AOC	Maintence Troubleshooting					
	AOC	FP Request/FP Data					
	AOC	Load Sheet Request/Transfer					
	AOC	Flight Log Transfer					
	AOC	Real Time Maintenance Info					
	AOC	Graphical Wx Info					
	AOC	Real Time Wx Report					
	AOC	Technical Logbook Update					
	AOC	Cabin Log Book Transfer					
	AOC	Update Electronic Library					
	AOC	Software Loading					

TABLE C–5.—Continued.

		COCR ATM Service	ATS G/A Broadcast Oceanic/Remote	ATS G/A Broadcast Polar	ATS G/A Broadcast Autonomous	ATS A/A Addressed Airport	ATS A/A Addressed TMA
	ATS	**ATC** - Clearance (ACL)					
	ATS	**ATC** - Mic Check (AMC)	X	X			
	ATS	**ATC** - DL Taxi Clearance (D-TAXI)					
	ATS	**ATC** - Departure Clearance (DCL)					
	ATS	**ATC** - Downstream Clearance (DSC)					
	ATS	**ATC** - Pilot Preferences Downlink (PPD)					
	ATS	**ATC** - Dynamic Route Availability (DYNAV)					
	ATS	**ATC** - Arrival Manager Info (ARMAND)					
	ATS	**ATC** - Common Traject. Coord. (COTRAC)					
	ATS	**ATC** - Auto Execute (A-EXEC)					
	ATS	**Auto Downlink** - FP Consist. (FLIPCY)					
	ATS	**Auto Downlink** - FP Intent (FLIPINT)					
	ATS	**Auto Downlink** - System Access Param (SAP)					
	ATS	**Flight Info** - Operational Terminal Info (D-OTIS)					
	ATS	**Flight Info** - RVR (D-RVR)					
	ATS	**Flight Info** - Operational Enroute Info (D-ORIS)	X	X			
	ATS	**Flight Info** - Meterological Info (D-SIGMET)	X	X			
	ATS	**Flight Info** - Automatic Terminal Info (D-ATIS)					
	ATS	**Flight Info** - Flight Updates (D-FLUP)					
	ATS	**Flight Info** - Surface Info (D-SIG)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -ATC Surveillance (SURV)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -Enhanced Visual Acquisition (EVA)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Wake Broadcast (WAKE)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - In-Trail Procedures (ITP)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Crossing & Passing (C&P)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Sequencing & Merging (S&M)					
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Paired Approach (PAIRAPP)					X
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Air-to-Air Self Separation (AIRSEP)					
	ATS	**Emergency** - Urgent Contact (URCO)					
	ATS	**Emergency** - DL Alert (D-ALERT)					
	ATS	**Comm Mngt** - Data Link Login (DLL)					
	ATS	**Comm Mngt** - Comm Mngt (ACM)					
	ATS	**Comm Mngt** - Net Connect					
	ATS	**Comm Mngt** - Net Keep Alive					
	AOC	AOC Login					
	AOC	Out Off On In (OOOI)					
	AOC	NOTAM Request/NOTAMs					
	AOC	Free Text					
	AOC	Wx Request/Wx Report					
	AOC	Position Report					
	AOC	Flight Status					
	AOC	Fuel Status					
	AOC	Gate/Connections Status					
	AOC	Engine Performance Reports					
	AOC	Maintence Troubleshooting					
	AOC	FP Request/FP Data					
	AOC	Load Sheet Request/Transfer					
	AOC	Flight Log Transfer					
	AOC	Real Time Maintenance Info					
	AOC	Graphical Wx Info					
	AOC	Real Time Wx Report					
	AOC	Technical Logbook Update					
	AOC	Cabin Log Book Transfer					
	AOC	Update Electronic Library					
	AOC	Software Loading					

TABLE C–5.—Continued.

		COCR ATM Service	ATS A/A Addressed En Route	ATS A/A Addressed Oceanic/Remote	ATS A/A Addressed Polar	ATS A/A Addressed Autonomous	ATS Air Broadcast Airport
	ATS	**ATC** - Clearance (ACL)					
	ATS	**ATC** - Mic Check (AMC)					
	ATS	**ATC** - DL Taxi Clearance (D-TAXI)					
	ATS	**ATC** - Departure Clearance (DCL)					
	ATS	**ATC** - Downstream Clearance (DSC)					
	ATS	**ATC** - Pilot Preferences Downlink (PPD)					
	ATS	**ATC** - Dynamic Route Availability (DYNAV)					
	ATS	**ATC** - Arrival Manager Info (ARMAND)					
	ATS	**ATC** - Common Traject. Coord. (COTRAC)					
	ATS	**ATC** - Auto Execute (A-EXEC)					
	ATS	**Auto Downlink** - FP Consist. (FLIPCY)					
	ATS	**Auto Downlink** - FP Intent (FLIPINT)					
	ATS	**Auto Downlink** - System Access Param (SAP)					
	ATS	**Flight Info** - Operational Terminal Info (D-OTIS)					
	ATS	**Flight Info** - RVR (D-RVR)					
	ATS	**Flight Info** - Operational Enroute Info (D-ORIS)					
	ATS	**Flight Info** - Meterological Info (D-SIGMET)					
	ATS	**Flight Info** - Automatic Terminal Info (D-ATIS)					
	ATS	**Flight Info** - Flight Updates (D-FLUP)					
	ATS	**Flight Info** - Surface Info (D-SIG)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -ATC Surveillance (SURV)					X
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -Enhanced Visual Acquisition (EVA)					X
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Wake Broadcast (WAKE)					X
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - In-Trail Procedures (ITP)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Crossing & Passing (C&P)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Sequencing & Merging (S&M)					
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Paired Approach (PAIRAPP)					
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Air-to-Air Self Separation (AIRSEP)				X	
	ATS	**Emergency** - Urgent Contact (URCO)					
	ATS	**Emergency** - DL Alert (D-ALERT)					
	ATS	**Comm Mngt** - Data Link Login (DLL)					
	ATS	**Comm Mngt** - Comm Mngt (ACM)					
	ATS	**Comm Mngt** - Net Connect					
	ATS	**Comm Mngt** - Net Keep Alive					
	AOC	AOC Login					
	AOC	Out Off On In (OOOI)					
	AOC	NOTAM Request/NOTAMs					
	AOC	Free Text					
	AOC	Wx Request/Wx Report					
	AOC	Position Report					
	AOC	Flight Status					
	AOC	Fuel Status					
	AOC	Gate/Connections Status					
	AOC	Engine Performance Reports					
	AOC	Maintence Troubleshooting					
	AOC	FP Request/FP Data					
	AOC	Load Sheet Request/Transfer					
	AOC	Flight Log Transfer					
	AOC	Real Time Maintenance Info					
	AOC	Graphical Wx Info					
	AOC	Real Time Wx Report					
	AOC	Technical Logbook Update					
	AOC	Cabin Log Book Transfer					
	AOC	Update Electronic Library					
	AOC	Software Loading					

TABLE C–5.—Continued.

		COCR ATM Service	ATS Air Broadcast TMA	ATS Air Broadcast En Route	ATS Air Broadcast Oceanic/Remote	ATS Air Broadcast Polar	ATS Air Broadcast Autonomous
	ATS	**ATC** - Clearance (ACL)					
	ATS	**ATC** - Mic Check (AMC)					
	ATS	**ATC** - DL Taxi Clearance (D-TAXI)					
	ATS	**ATC** - Departure Clearance (DCL)					
	ATS	**ATC** - Downstream Clearance (DSC)					
	ATS	**ATC** - Pilot Preferences Downlink (PPD)					
	ATS	**ATC** - Dynamic Route Availability (DYNAV)					
	ATS	**ATC** - Arrival Manager Info (ARMAND)					
	ATS	**ATC** - Common Traject. Coord. (COTRAC)					
	ATS	**ATC** - Auto Execute (A-EXEC)					
	ATS	**Auto Downlink** - FP Consist. (FLIPCY)					
	ATS	**Auto Downlink** - FP Intent (FLIPINT)					
	ATS	**Auto Downlink** - System Access Param (SAP)					
	ATS	**Flight Info** - Operational Terminal Info (D-OTIS)					
	ATS	**Flight Info** - RVR (D-RVR)					
	ATS	**Flight Info** - Operational Enroute Info (D-ORIS)					
	ATS	**Flight Info** - Meterological Info (D-SIGMET)					
	ATS	**Flight Info** - Automatic Terminal Info (D-ATIS)					
	ATS	**Flight Info** - Flight Updates (D-FLUP)					
	ATS	**Flight Info** - Surface Info (D-SIG)					
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -ATC Surveillance (SURV)	X	X	X	X	
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) -Enhanced Visual Acquisition (EVA)	X	X	X	X	
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Wake Broadcast (WAKE)	X	X	X	X	
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - In-Trail Procedures (ITP)		X	X	X	
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Crossing & Passing (C&P)		X	X	X	
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Sequencing & Merging (S&M)		X	X	X	
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Paired Approach (PAIRAPP)					
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Air-to-Air Self Separation (AIRSEP)					
	ATS	**Emergency** - Urgent Contact (URCO)					
	ATS	**Emergency** - DL Alert (D-ALERT)					
	ATS	**Comm Mngt** - Data Link Login (DLL)					
	ATS	**Comm Mngt** - Comm Mngt (ACM)					
	ATS	**Comm Mngt** - Net Connect					
	ATS	**Comm Mngt** - Net Keep Alive					
	AOC	AOC Login					
	AOC	Out Off On In (OOOI)					
	AOC	NOTAM Request/NOTAMs					
	AOC	Free Text					
	AOC	Wx Request/Wx Report					
	AOC	Position Report					
	AOC	Flight Status					
	AOC	Fuel Status					
	AOC	Gate/Connections Status					
	AOC	Engine Performance Reports					
	AOC	Maintence Troubleshooting					
	AOC	FP Request/FP Data					
	AOC	Load Sheet Request/Transfer					
	AOC	Flight Log Transfer					
	AOC	Real Time Maintenance Info					
	AOC	Graphical Wx Info					
	AOC	Real Time Wx Report					
	AOC	Technical Logbook Update					
	AOC	Cabin Log Book Transfer					
	AOC	Update Electronic Library					
	AOC	Software Loading					

TABLE C–5.—Concluded.

		COCR ATM Service	AOC A/G & G/A Addressed Airport	AOC A/G & G/A Addressed TMA	AOC A/G & G/A Addressed En Route	AOC A/G & G/A Addressed Remote/Oceanic/Polar
	ATS	**ATC** - Clearance (ACL)				
	ATS	**ATC** - Mic Check (AMC)				
	ATS	**ATC** - DL Taxi Clearance (D-TAXI)				
	ATS	**ATC** - Departure Clearance (DCL)				
	ATS	**ATC** - Downstream Clearance (DSC)				
	ATS	**ATC** - Pilot Preferences Downlink (PPD)				
	ATS	**ATC** - Dynamic Route Availability (DYNAV)				
	ATS	**ATC** - Arrival Manager Info (ARMAND)				
	ATS	**ATC** - Common Traject. Coord. (COTRAC)				
	ATS	**ATC** - Auto Execute (A-EXEC)				
	ATS	**Auto Downlink** - FP Consist. (FLIPCY)				
	ATS	**Auto Downlink** - FP Intent (FLIPINT)				
	ATS	**Auto Downlink** - System Access Param (SAP)				
	ATS	**Flight Info** - Operational Terminal Info (D-OTIS)				
	ATS	**Flight Info** - RVR (D-RVR)				
	ATS	**Flight Info** - Operational Enroute Info (D-ORIS)				
	ATS	**Flight Info** - Meterological Info (D-SIGMET)				
	ATS	**Flight Info** - Automatic Terminal Info (D-ATIS)				
	ATS	**Flight Info** - Flight Updates (D-FLUP)				
	ATS	**Flight Info** - Surface Info (D-SIG)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) - ATC Surveillance (SURV)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation Awareness (ATSA) - Enhanced Visual Acquisition (EVA)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Wake Broadcast (WAKE)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - In-Trail Procedures (ITP)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Crossing & Passing (C&P)				
ADS-B	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Sequencing & Merging (S&M)				
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Paired Approach (PAIRAPP)				
	ATS	**Traffic/Surv** - Airborne Separation (ASAS) - Air-to-Air Self Separation (AIRSEP)				
	ATS	**Emergency** - Urgent Contact (URCO)				
	ATS	**Emergency** - DL Alert (D-ALERT)				
	ATS	**Comm Mngt** - Data Link Login (DLL)				
	ATS	**Comm Mngt** - Comm Mngt (ACM)				
	ATS	**Comm Mngt** - Net Connect				
	ATS	**Comm Mngt** - Net Keep Alive				
	AOC	AOC Login	X			X
	AOC	Out Off On In (OOOI)	X			
	AOC	NOTAM Request/NOTAMs	X		X	X
	AOC	Free Text			X	X
	AOC	Wx Request/Wx Report	X		X	X
	AOC	Position Report		X	X	X
	AOC	Flight Status	X	X	X	X
	AOC	Fuel Status			X	X
	AOC	Gate/Connections Status			X	
	AOC	Engine Performance Reports		X	X	
	AOC	Maintence Troubleshooting			X	X
	AOC	FP Request/FP Data	X		X	X
	AOC	Load Sheet Request/Transfer	X	X		
	AOC	Flight Log Transfer	X			
	AOC	Real Time Maintenance Info			X	X
	AOC	Graphical Wx Info	X		X	X
	AOC	Real Time Wx Report	X	X	X	X
	AOC	Technical Logbook Update	X			
	AOC	Cabin Log Book Transfer	X			
	AOC	Update Electronic Library	X			
	AOC	Software Loading	X			

Note in the table above, shading identifies those COCR services and associated communication functions that are not in the scope of the technology evaluation; the services and communication functions is addressed by ADS-B technologies.

In addition to functional needs, technical evaluation criteria also address required performance. As noted in section C.1, four types of performance criteria were defined for technology evaluation. These criteria and associated traceability are provided in table C–6.

TABLE C–6.—TRACEABILITY OF TECHNICAL PERFORMANCE EVALUATION CRITERIA

COCR Section		Requirements	Criterion
Section 5 Operational Performance Requirements	5.4 FRS Allocated Data Performance Requirements	Table 5–6 FRS Allocated Data Performance (ATS) – Phase 1	Latency
	5.4 FRS Allocated Data Performance Requirements	Table 5–7 FRS Allocated Data Performance (ATS) – Phase 2	Latency
	5.4 FRS Allocated Data Performance Requirements	Table 5–8 FRS Allocated Data Performance (AOC) – Phase 1 & 2	Latency
	5.5 FRS Data Classes of Service	Table 5–9 Data COS (Type DG – A/G Addressed); Table 5-10 Data COS (Type DA – A/A Addressed); Table 5-11 Data COS (Type DB – A/A Broadcast);	QoS Priority
	5.5 FRS Data Classes of Service	Table 5–12 COS Assignments (Network Management) – Phase 1 & 2; Table 5-13 COS Assignments (ATS) – Phase 1 & 2; Table 5-14 COS Assignments (AOC) – Phase 1 & 2	QoS Priority
	5.6 Voice Requirements	Table 5–15 Voice Performance Requirements (ATS) – Phases 1 & 2; Table 5–16 Voice Performance Requirements (AOC) – Phase 1 & 2	N/A
Section 6 Communication Loading Analysis	6.2.2 Peak Counts	Table 6–1 PIAC Projections for High Density and Low Density Service Volumes	Number of Users
	6.3 Voice Loading Analysis	Table 6–17 Voice Capacity Requirements – Phase 1; Table 6-28 Voice Capacity Requirements – Phase 2	N/A
	6.4 Air/Ground Data Capacity Analysis	Table 6–19 A/G Capacity Requirements – Phase 1; Table 6-20 A/G Capacity Requirements – Phase 2; Table 6–21 A/G Capacity Requirements excluding A-EXEC service – Phase 2;	Data Rate
	6.4 Air/Ground Data Capacity Analysis	Table 6–22 A/G Capacity Requirements for each Aircraft using a Separate 'Channel' – Phase 1;Table 6–23 A/G Capacity Requirements for each Aircraft using a Separate 'Channel' – Phase 2;Table 6–24 A/G Capacity Requirements for each Aircraft using a Separate 'Channel' excluding the A-EXEC service – Phase 2	Data Rate

C.2.2 Technology Evaluation Criteria and Traceability

Table C–7 provides a full set of derived technology evaluation criteria and associated traceability.

TABLEC–7.—TECHNOLOGY EVALUATION CRITERIA AND TRACEABILITY

	Evaluation Criterion	Description (& sub-items)	Traceability
1	Technical Readiness Level	Provides an indication of the technical maturity of the proposed technology (Technical Readiness Level)	11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 2
2	Standardization Status	Indicates the relevance and maturity of a proposed technologies standardization status.	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 3
3	Certifiability	Provides a relative measure of the candidate complexity.	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 3
4	Ground Infrastructure Cost	Estimates cost to service provider to provide coverage to a geographically large sector.	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 4
5	Cost to Aircraft	Estimates relative cost to upgrade avionics with new technology.	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (5.14) 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5 – Number 4
6	Spectrum Protection	Gauges the likelihood of obtaining the proper allocation of the target spectrum.	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)
7	Security – A&I	Assesses whether authentication and data integrity are provided	COCR Security Requirements (table 4–11) Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-8)
8	Security – Robustness to Jamming	Assesses technology resistance to jamming.	COCR Security Requirements (table 4–11)
9	Transition	Assesses acceptable transition characteristics, including: return on partial investment ease of technical migration (spectral, physical) ease of operational migration (air and ground users)	Global Air Navigation Plan for CNS/ATM Systems – ICAO Doc 9750 (Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation, appendix A to Chapter 2, pg I-2-7)

APPENDIX D. COCR PERFORMANCE REQUIREMENTS AND INSTITUTIONAL CRITERIA EVALUATION METRICS

This appendix serves two purposes. First, it documents the COCR version 1 requirements used in the assessment of technologies (in AHP step 6). Second, it documents the institutional criteria evaluation metrics defined in the 2004 FCS technology pre-screening study that have been used for technology assessment (in AHP step 6). The information noted above is provided in the following two subsections.

D.1 Documentation of COCR Performance Requirements

The COCR includes 13 tables that document latency, QoS, and data capacity requirements for defined COCR services for Phases 1 and 2 operational concepts. Specifically, these COCR tables include:

- TableD–1 FRS Allocated Data Performance (ATS)—COCR Phase 1
- Table D–2 FRS Allocated Data Performance (ATS)—COCR Phase 2
- Table D–3 FRS Allocated Data Performance (AOC)—COCR Phases 1 and 2
- Table D–4 Data COS (Type DG—A/G Addressed)
- Table D–5 Data COS (Type DA—A/A Addressed)
- Table D–6 Data COS (Type DB—A/A Broadcast)
- Table D–7 COS Assignments (Network Management)—COCR Phases 1 and 2
- Table D–8 COS Assignments (ATS)—COCR Phases 1 and 2
- Table D–9 COS Assignments (AOC)—COCR Phases 1 and 2
- Table D–10 PIAC Projections for High Density and Low Density Service Volumes
- Table D–11 A/G Capacity Requirements—COCR Phase 1
- Table D–12 A/G Capacity Requirements—COCR Phase 2
- Table D–13 A/G Capacity Requirements—Excluding A-EXEC service COCR Phase 2

These tables have been reprinted in this document as a reference. The tables are provided in the same order as presented above, beginning with Table D–1. All tables are provided below.

TABLE D–1.—FRS ALLOCATED DATA PERFORMANCE (ATS)—COCR PHASE 1

Service	Latency (RCTP - 1 way)					Integrity	Availability	
	APT	TMA	ENR	ORP	AOA			
	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$
ACL	3.8	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965
ACM	3.8	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965
ADS-B	0.80	4.8	9.6	9.6	-	5.0E-6	0.9995	0.9965
A-EXEC	-	-	-	-	-	-	-	-
AIRSEP	-	-	-	-	-	-	-	-
AMC	3.8	3.8	3.8	26.5	-	5.0E-4	0.9995	0.9965
ARMAND	-	-	9.2	-	-	5.0E-6	0.9995	0.9965
C&P	-	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965
COTRAC	-	-	-	-	-	-	-	-
D-ALERT	3.8	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965
D-ATIS	9.2	9.2	9.2	26.5	-	5.0E-6	0.9995	0.9965
DCL	9.2	-	-	-	-	5.0E-6	0.9995	0.9965
D-FLUP	9.2	-	-	-	-	5.0E-6	0.9995	0.9965
DLL	5.6	5.6	5.6	26.5	-	5.0E-6	0.9995	0.9965
D-ORIS	-	9.2	9.2	26.5	-	5.0E-6	0.9995	0.9965
D-OTIS	9.2	9.2	9.2	26.5	-	5.0E-6	0.9995	0.9965
D-RVR	4.7	4.7	9.2	26.5	-	5.0E-6	0.9995	0.9965
DSC	-	-	22.2	26.5	-	5.0E-6	0.9995	0.9965
D-SIG	9.2	9.2	-	-	-	5.0E-6	0.9995	0.9965
D-SIGMET	9.2	9.2	9.2	26.5	-	5.0E-6	0.9995	0.9965
D-TAXI	3.8	3.8	-	-	-	5.0E-6	0.9995	0.9965
DYNAV	-	-	-	-	-	-	-	-
FLIPCY	13.6	13.6	13.6	26.5	-	5.0E-6	0.9995	0.9965
FLIPINT	13.6	13.6	13.6	26.5	-	5.0E-6	0.9995	0.9965
ITP	-	-	-	26.5	-	5.0E-6	0.9995	0.9965
PAIRAPP	-	-	-	-	-	-	-	-
PPD	13.6	13.6	13.6	26.5	-	5.0E-6	0.9995	0.9965
S&M	-	3.8	3.8	-	-	5.0E-6	0.9995	0.9965
SAP	-	4.7	4.7	-	-	5.0E-6	0.9995	0.9965
TIS-B	0.80	4.8	9.6	9.6	-	5.0E-6	0.9995	0.9965
URCO	-	-	-	-	-	-	-	-
WAKE	0.80	4.8	9.6	9.6	-	5.0E-6	0.9995	0.9965

TABLE D–2.—FRS ALLOCATED DATA PERFORMANCE (ATS)—COCR PHASE 2

Service	Latency (RCTP - 1 way)					Integrity	Availability	
	APT	TMA	ENR	ORP	AOA			
	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$
ACL	1.4	1.4	1.4	1.4	1.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
ACM	1.4	1.4	1.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
ADS-B	0.8	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
A-EXEC	-	0.74	0.74	0.74	-	5.0E-10	1-(5.0E-10)	1-(5.0E-8)
AIRSEP	-	-	-	-	8.0	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
AMC	1.4	1.4	1.4	1.4	1.4	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
ARMAND	-	-	4.7	-	-	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
C&P	-	2.4	2.4	2.4	-	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
COTRAC	-	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
D-ALERT	2.4	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
D-ATIS	2.4	2.4	4.7	9.2	9.2	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
DCL	2.4	-	-	-	-	5.0E-8	1-(5.0E-5)	1-(5.0E-4)
D-FLUP	2.4	-	-	-	-	5.0E-5	1-(5.0E-4)	1-(5.0E-3)
DLL	1.4	2.4	4.7	9.2	9.2	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
D-ORIS	-	2.4	4.7	9.2	9.2	5.0E-5	1-(5.0E-4)	1-(5.0E-3)
D-OTIS	2.4	2.4	2.4	9.2	9.2	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
D-RVR	1.4	1.4	4.7	9.2	9.2	5.0E-6	1-(5.0E-4)	1-(5.0E-3)
DSC	-	-	2.4	4.7	4.7	5.0E-8	1-(5.0E-5)	1-(5.0E-4)
D-SIG	4.7	4.7	-	-	-	5.0E-8	1-(5.0E-5)	1-(5.0E-4)
D-SIGMET	2.4	2.4	2.4	4.7	9.2	5.0E-8	1-(5.0E-5)	1-(5.0E-4)
D-TAXI	2.4	2.4	-	-	-	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
DYNAV	-	-	4.7	9.2	-	5.0E-6	1-(5.0E-5)	1-(5.0E-4)
FLIPCY	2.4	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
FLIPINT	2.4	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
ITP	-	2.4	2.4	2.4	-	5.0E-6	1-(5.0E-8)	1-(5.0E-6)
PAIRAPP	0.24	0.24	-	-	-	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
PPD	4.7	4.7	4.7	4.7	4.7	5.0E-8	1-(5.0E-4)	1-(5.0E-3)
S&M	-	2.4	2.4	2.4	-	5.0E-4	1-(5.0E-8)	1-(5.0E-6)
SAP	-	2.4	2.4	-	-	5.0E-8	1-(5.0E-5)	1-(5.0E-4)
TIS-B	-	-	-	-	-	-	-	--
URCO	1.4	1.4	1.4	1.4	1.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
WAKE	0.8	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)

TABLE D–3.—FRS ALLOCATED DATA PERFORMANCE (AOC)—COCR PHASES 1 AND 2

Service	Latency (RCTP - 1 way)					Integrity	Availability	
	APT	TMA	ENR	ORP	AOA[3]			
	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$
AOCDLL	13.6	13.6	13.6	26.5	26.5	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
CABINLOG	26.5	-	-	-	-	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
ENGINE	26.5	26.5	26.5	51.7	51.7	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
FLTLOG	26.5	-	-	-	-	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
FLTPLAN	13.6	13.6	13.6	26.5	26.5	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
FLTSTAT	13.6	13.6	13.6	26.5	26.5	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
FREETXT	26.5	26.5	26.5	51.7	51.7	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
FUEL	26.5	26.5	26.5	51.7	51.7	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
GATES	13.6	13.6	13.6	26.5	26.5	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
LOADSHT	13.6	13.6	-	-	-	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
MAINTPR	13.6	13.6	13.6	26.5	26.5	5.0E-5	1-(5.0E-4)	1-(5.0E-3)
MAINTRT	26.5	26.5	26.5	51.7	51.7	5.0E-5	1-(5.0E-4)	1-(5.0E-3)
NOTAM	26.5	26.5	26.5	51.7	51.7	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
OOOI	13.6	-	-	-	-	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
POSRPT	26.5	26.5	26.5	51.7	51.7	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
SWLOAD	26.5	26.5	26.5	51.7	51.7	5.0E-4	1-(5.0E-4)	1-(5.0E-3)
TECHLOG	26.5	-	-	-	-	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
UPLIB	26.5	26.5	26.5	51.7	51.7	5.0E-8	1-(5.0E-5)	1-(5.0E-4)
WXGRAPH	13.6	13.6	13.6	26.5	26.5	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
WXRT	13.6	13.6	13.6	26.5	26.5	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
WXTEXT	13.6	13.6	13.6	26.5	26.5	5.0E-5	1-(5.0E-4)	1-(5.0E-3)

TABLE D–4.—DATA COS (TYPE DG—A/G ADDRESSED)

COS	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$	Service Type
DG-A	9.8	5.0E-8	1-(5.0E-8)	1-(5.0E-6)	System/Network
DG-B	0.74	5.0E-10	1-(5.0E-10)	1-(5.0E-8)	ATS A/G Data
DG-C	1.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)	
DG-D	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)	
DG-E	3.8	5.0E-6	0.9995	0.9965	
DG-F	4.7	5.0E-8	1-(5.0E-5)	1-(5.0E-4)	
DG-G	9.2	5.0E-6	0.9995	0.9965	
DG-H	13.6	5.0E-6	0.9995	0.9965	
DG-I	26.5	5.0E-6	0.9995	0.9965	
DG-J	13.6	5.0E-8	1-(5.0E-6)	1-(5.0E-5)	AOC A/G Data
DG-K	26.5	5.0E-8	1-(5.0E-5)	1-(5.0E-4)	
DG-L	51.7	5.0E-8	1-(5.0E-5)	1-(5.0E-4)	

TABLE D–5.—DATA COS (TYPE DA—A/A ADDRESSED)

COS	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$	Service Type
DA-A	rsvd	rsvd	rsvd	rsvd	System/Network
DA-B	0.24	5.00E-08	1-(5.0E-8)	1-(5.0E-6)	ATS A/A Data
DA-C	8	5.00E-08	1-(5.0E-8)	1-(5.0E-6)	

TABLE D–6.—DATA COS (TYPE DB—A/A BROADCAST)

COS	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$	Service Type
DB-A	0.8	5.00E-08	1-(5.0E-8)	1-(5.0E-6)	ADS-B/TIS-B/ WAKE Broadcast Data
DB-B	2.4	5.00E-08	1-(5.0E-8)	1-(5.0E-6)	
DB-C	0.8	5.0E-6	0.9995	0.9965	
DB-D	4.8	5.0E-6	0.9995	0.9965	
DB-E	9.6	5.0E-6	0.9995	0.9965	

TABLE D–7.—COS ASSIGNMENTS (NETWORK MANAGEMENT)—COCR PHASES 1 AND 2

Service	Phase 1 & 2				
	APT	TMA	ENR	ORP	AOA [4]
NETCONN	DG-A	DG-A	DG-A	DG-A	DG-A
NETKEEP	DG-A	DG-A	DG-A	DG-A	DG-A

TABLE D–8.—COS ASSIGNMENTS (ATS)—COCR PHASES 1 AND 2

Service	Phase 1					Phase 2				
	APT	TMA	ENR	ORP	AOA	APT	TMA	ENR	ORP	AOA
ACL	DG-E	DG-E	DG-E	DG-I	-	DG-C	DG-C	DG-C	DG-C	DG-C
ACM	DG-E	DG-E	DG-E	DG-I	-	DG-C	DG-C	DG-C	DG-D	DG-D
ADS-B	DB-C	DB-D	DB-E	DB-E	-	DB-A	DB-B	DB-B	DB-B	DB-B
A-EXEC	-	-	-	-	-	-	DG-B	DG-B	DG-B	-
AIRSEP	-	-	-	-	-	-	-	-	-	DA-C
AMC	DG-E	DG-E	DG-E	DG-I	-	DG-C	DG-C	DG-C	DG-C	DG-C
ARMAND	-	-	DG-G	-	-	-	-	DG-D	-	-
C&P	-	DG-E	DG-E	DG-I	-	-	DG-D	DG-D	DG-D	-
COTRAC	-	-	-	-	-	DG-D	DG-D	DG-D	DG-D	DG-D
D-ALERT	DG-E	DG-E	DG-E	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
D-ATIS	DG-G	DG-G	DG-G	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
DCL	DG-G	-	-	-	-	DG-D	-	-	-	-
D-FLUP	DG-G	-	-	-	-	DG-D	-	-	-	-
DLL	DG-E	DG-E	DG-E	DG-I	-	DG-C	DG-D	DG-D	DG-D	DG-D
D-ORIS	-	DG-G	DG-G	DG-I	-	-	DG-D	DG-D	DG-D	DG-D
D-OTIS	DG-G	DG-G	DG-G	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
D-RVR	DG-E	DG-E	DG-G	DG-I	-	DG-C	DG-C	DG-D	DG-D	DG-D
DSC	-	-	DG-H	DG-I	-	-	-	DG-D	DG-D	DG-D
D-SIG	DG-G	DG-G	-	-	-	DG-F	DG-D	-	-	-
D-SIGMET	DG-G	DG-G	DG-G	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
D-TAXI	DG-E	DG-E	-	-	-	DG-D	DG-D	-	-	-
DYNAV	-	-	-	-	-	-	-	DG-D	DG-D	-
FLIPCY	DG-H	DG-H	DG-H	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
FLIPINT	DG-H	DG-H	DG-H	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
ITP	-	-	-	DG-I	-	-	DG-D	DG-D	DG-D	-
PAIRAPP	-	-	-	-	-	DA-B	DA-B	-	-	-
PPD	DG-H	DG-H	DG-H	DG-I	-	DG-D	DG-D	DG-D	DG-D	DG-D
S&M	-	DG-E	DG-E	-	-	-	DG-D	DG-D	DG-D	-
SAP	-	DG-E	DG-E	-	-	-	DG-D	DG-D	-	-
TIS-B	DB-C	DB-D	DB-E	DB-E	-	-	-	-	-	-
URCO	-	-	-	-	-	DG-C	DG-C	DG-C	DG-C	DG-C
WAKE	DB-C	DB-D	DB-E	DB-E	-	DB-A	DB-B	DB-B	DB-B	DB-B

TABLE D–9.—COS ASSIGNMENTS (AOC)—
COCR PHASES 1 AND 2

Service	Phase 1 & 2				
	APT	TMA	ENR	ORP	AOA[5]
AOCDLL	DG-J	DG-J	DG-J	DG-K	DG-K
CABINLOG	DG-K	-	-	-	-
ENGINE	DG-K	DG-K	DG-K	DG-L	DG-L
FLTLOG	DG-K	-	-	-	-
FLTPLAN	DG-J	DG-J	DG-J	DG-K	DG-K
FLTSTAT	DG-J	DG-J	DG-J	DG-K	DG-K
FREETXT	DG-K	DG-K	DG-K	DG-L	DG-L
FUEL	DG-K	DG-K	DG-K	DG-L	DG-L
GATES	DG-J	DG-J	DG-J	DG-K	DG-K
LOADSHT	DG-J	DG-J	-	-	-
MAINTPR	DG-J	DG-J	DG-J	DG-K	DG-K
MAINTRT	DG-K	DG-K	DG-K	DG-L	DG-L
NOTAM	DG-K	DG-K	DG-K	DG-L	DG-L
OOOI	DG-J	-	-	-	-
POSRPT	DG-K	DG-K	DG-K	DG-L	DG-L
SWLOAD	DG-K	DG-K	DG-K	DG-L	DG-L
TECHLOG	DG-K	-	-	-	-
UPLIB	DG-K	DG-K	DG-K	DG-L	DG-L
WXGRAPH	DG-J	DG-J	DG-J	DG-K	DG-K
WXRT	DG-J	DG-J	DG-J	DG-K	DG-K
WXTEXT	DG-J	DG-J	DG-J	DG-K	DG-K

TABLE D–10.—PIAC PROJECTIONS FOR HIGH- AND LOW-DENSITY SERVICE VOLUMES

Scenario	Date	APT		TMA		ENR		ONR		AOA
		HD	LD	HD	LD	HD	LD	HD	LD	
ECAC	2020	-	-	16	14	24	24	-	-	-
NAS	2020	200	12	-	-	41	-	10	5	-
ECAC	2030	-	-	44	39	45	59[6]	-	-	-
NAS	2030	290	19	-	-	95	-	34	18	70

TABLE D–11.—A/G CAPACITY REQUIREMENTS—COCR PHASE 1

PHASE 1		APT SV HD	APT SV LD	TMA SV HD	TMA SV LD	ENR SV HD EU	ENR SV HD US	ENR SV LD	ORP SV HD	ORP SV LD
Separate ATS	UL	4.0	1.2	2.3	2.2	1.2	1.5	1.2	0.3	0.3
	DL	4.3	1.9	4.1	3.9	3.7	4.9	3.7	2.7	2.2
	UL&DL	7.4	2.0	5.3	5.0	4.1	5.6	4.1	2.8	2.2
Separate AOC	UL	15.6	2.7	0.3	0.3	8.6	11.9	8.6	3.3	2.8
	DL	3.5	0.7	0.8	0.8	0.8	1.3	0.8	0.4	0.3
	UL&DL	19.9	2.9	0.8	0.8	9.1	13.8	9.1	3.3	2.8
Combined ATS&AOC	UL	18.4	2.9	2.3	2.2	9.0	12.7	8.9	3.3	2.8
	DL	6.7	2.0	4.3	4.1	3.8	5.2	3.8	2.7	2.2
	UL&DL	25.5	3.3	5.6	5.3	11.4	17.7	11.3	4.5	3.4

TABLE D–12.—A/G CAPACITY REQUIREMENTS—COCR PHASE 2

PHASE 2		APT SV HD	APT SV LD	TMA SV HD	TMA SV LD	ENR SV HD EU	ENR SV HD US	ENR SV LD	ORP SV HD	ORP SV LD	AOA
Separate ATS	UL	12.8	7.1	22.0	22.2	20.9	22.4	21.0	19.8	19.6	7.1
	DL	11.3	5.2	10.3	10.7	9.8	13.5	10.5	8.9	8.7	13.3
	UL&DL	19.6	7.3	24.5	25.1	23.5	27.0	24.0	20.3	19.9	13.6
Separate AOC	UL	113.0	14.1	0.3	0.2	52.4	96.1	64.1	24.0	18.2	56.2
	DL	6.7	1.2	2.4	2.2	1.4	2.7	1.8	0.6	0.4	1.1
	UL&DL	131.2	14.1	2.6	2.3	58.6	106.9	72.6	24.4	18.2	62.8
Combined ATS&AOC	UL	120.0	24.6	22.0	22.2	119.1	168.3	134.8	82.1	62.8	76.7
	DL	13.4	5.4	11.1	11.8	10.2	13.9	10.9	9.0	8.8	13.4
	UL&DL	144.3	24.8	25.2	25.8	119.4	168.9	135.2	82.2	62.9	80.5

TABLE D–13.—A/G CAPACITY REQUIREMENTS—EXCLUDING A-EXEC SERVICE COCR PHASE 2

PHASE 2		APT SV HD	APT SV LD	TMA SV HD	TMA SV LD	ENR SV HD EU	ENR SV HD US	ENR SV LD	ORP SV HD	ORP SV LD	AOA
Separate ATS	UL	12.8	7.1	9.2	9.2	7.4	9.4	7.1	6.0	5.9	7.1
	DL	11.3	5.2	10.3	10.7	9.7	13.2	10.1	8.9	8.7	13.3
	UL&DL	19.6	7.3	16.6	16.8	11.8	17.8	12.5	9.2	8.9	13.6
Separate AOC	UL	113.0	14.1	0.3	0.4	52.4	96.1	64.1	24.0	18.2	56.2
	DL	6.7	1.2	2.4	2.5	1.4	2.7	1.8	0.6	0.4	1.1
	UL&DL	131.2	14.1	2.6	2.7	58.6	106.9	72.6	24.4	18.2	62.8
Combined ATS&AOC	UL	120.0	24.6	9.2	9.2	80.1	116.1	91.6	53.0	38.7	76.7
	DL	13.4	5.4	10.9	11.3	9.9	13.4	10.4	9.0	8.8	13.4
	UL&DL	144.3	24.8	17.0	17.3	80.4	117.4	92.0	53.1	38.8	80.5

D.2 Documentation of Institutional Criteria Evaluation Metrics

The following material documenting the metrics applied to evaluate institutional technology evaluation criteria has been extracted in whole from section 2.2 of the 2004 Technology Pre-Screening report (Technology Assessment for the Future Aeronautical Communication System).[133] It is provided here as a reference because the same metrics have been used in the current technology analysis.

D.2.1 Technology Readiness Level (TRL)

The TRL scale was used as a criterion to evaluate the technical maturity of a candidate technology. The TRL scale as an evaluation of the readiness of technologies was pioneered by NASA and has been adopted by the DoD. The TRL is a measure of the gap between a technology's current maturity and the maturity needed for successful implementation. The TRL scale, illustrated in figure D–1, ranges from 1 to 9, based upon objective criteria. In figure D–2, the TRL is compared and mapped to the FAA's Implementation Readiness Level (IRL) and indicates what needs to be done and a time schedule from a given TRL to an operational system.

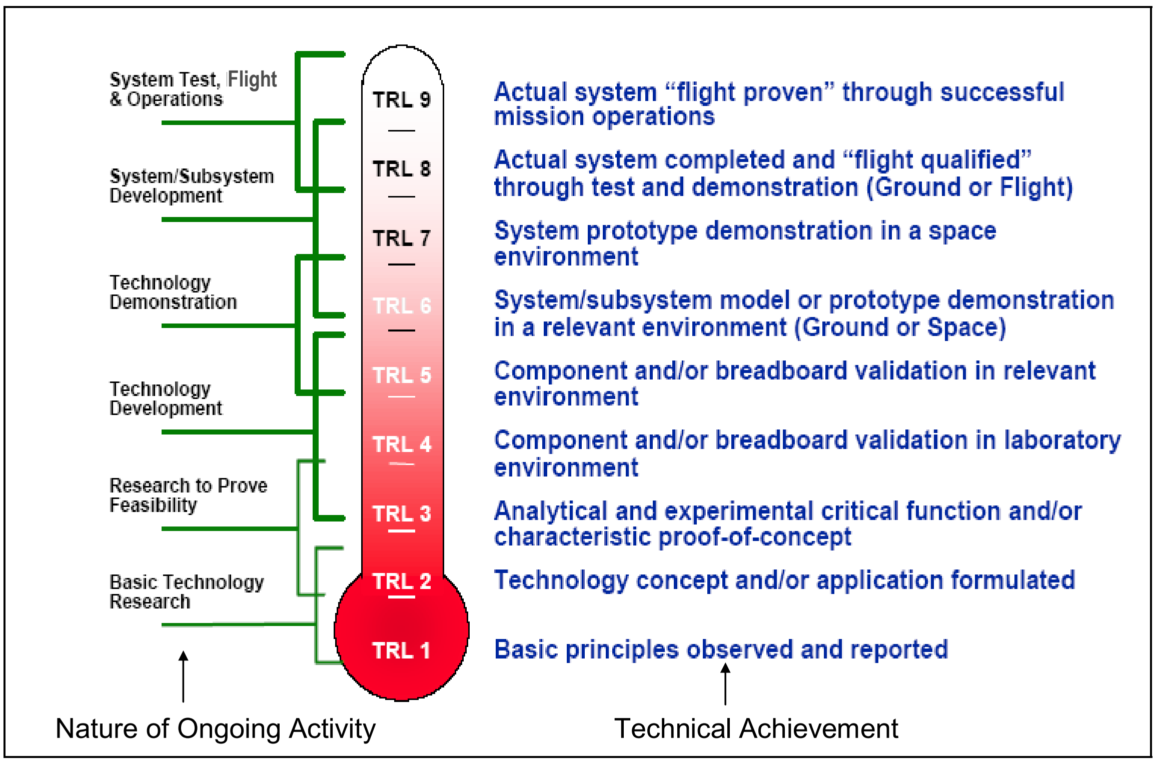


Figure D–1.—Technology Readiness Level Scale.

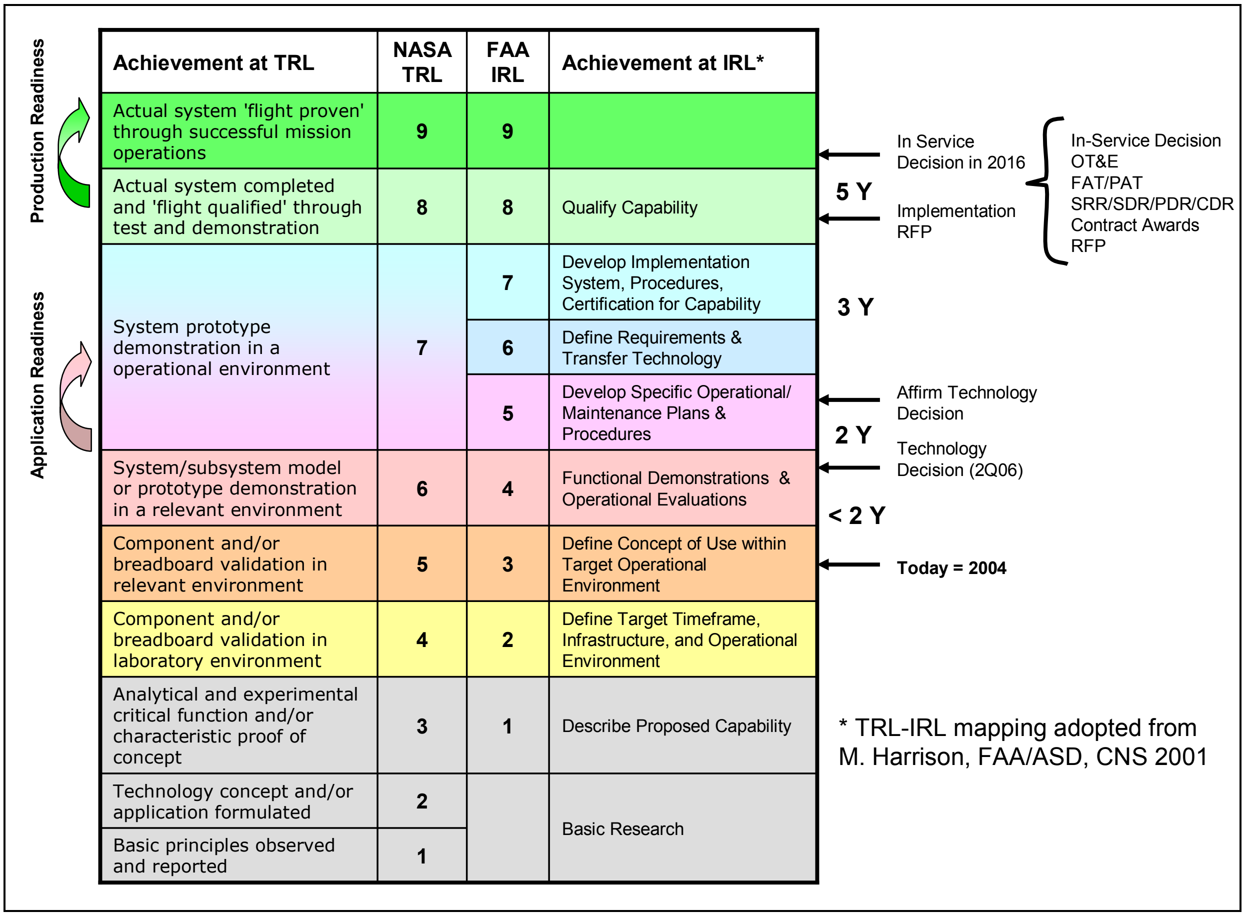


Figure D–2.—TRL and IRL Scales Compared.

The TRL criterion was used in this study to evaluate the technical maturity in the aeronautical environment. Table D–14 describes how the TRL is mapped into the evaluation colors.

TABLE D–14.—TECHNOLOGY READINESS LEVEL

Technology Readiness Level
[G, Y, or R status is assigned by assessing the TRL of the proposed candidate.] **Assessed as:** Green is a TRL 6 or above Yellow is TRL 5-4 Red is TRL 3 and below

D.2.2 Standardization

Table D–15 illustrates how the standardization status was used and mapped into the evaluation colors.

TABLE D–15.—STANDARDIZATION

Standardization Status
[G, Y, or R status is assigned based upon the existence of applicable standards for the candidate] **Assessed as:** Green: candidates that have a publicly available aeronautical standard; Yellow: candidates are supported by a mature commercial standard Red: candidates for which a supporting standard does not exist or is not publicly available

D.2.3 Certification

Table D–16 illustrates how the certification status was used and mapped into the evaluation colors.

TABLE D–16.—CERTIFICATION

Certifiability
Measure of certification risk **<u>Assessed as:</u>** Green: Candidates developed for the aviation industry and either currently certified or known to be in the certification process Yellow: Candidates developed for safety related services (Public safety and similar services) but not currently in the aviation certification process Red: All other candidates

D.2.4 Cost: A/G Communications Infrastructure

Table D–17 illustrates how the estimate of infrastructure cost was used and mapped into the evaluation colors.

TABLE D–17.—COST: A/G INFRASTRUCTURE

A/G Infrastructure Cost
Relative cost to replace or upgrade infrastructure with the necessary availability and diversity requirements for critical services, as a replacement to VHF DSB-AM; where applicable, replacement of a ground station covering a large area (e.g., high en route sector) should be assessed. Thus, a candidate not able to project a signal at a large range from a single ground station would require multiple replacement ground stations. This naturally penalizes candidates that cannot practically project a signal at a large range. The evaluation will include any unusual maintenance requirements of a candidate (to include leased services, maintenance of Network Operational Centers, extraordinary Telco bandwidth requirements and the like). <u>Assessed as:</u> Green: low relative cost, Yellow: moderate relative cost, Red: high relative cost

D.2.5 Cost: Avionics

Table D–18 illustrates how the estimate of avionics cost was used and mapped into the evaluation colors.

TABLE D–18.—COST: AVIONICS

Cost to Aircraft
Relative cost to upgrade avionics with new candidate data link technology but maintain VHF DSB-AM capability; **<u>Assessed as:</u>** Green: low relative cost Yellow: moderate relative cost Red: high relative cost

D.2.6 Spectrum Protection

Table D–19 illustrates how the spectrum status was used and mapped into the evaluation colors. The evaluation pertains to the likelihood that the targeted spectrum for a candidate technology will be available for aeronautical communications.

TABLE D–19.—SPECTRUM PROTECTION

Spectrum Protection
[G, Y, or R status is assigned based upon the extent to which the potential frequency bands are consistent with aeronautical safety critical communications] **<u>Assessed as:</u>** Green: the target band for the alternative has a global allocation for the Aeronautical Mobile (route) Service (AM(R)S) for ground-based systems or Aeronautical Mobile Satellite (route) Service (AMS(R)S) for satellite-based systems, as applicable Yellow: it can be reasonably expected that an additional global allocation (AM(R)S for terrestrial or AMS(R)S for satellite-based) could be added to the target band or if the band is shared with other aviation systems, it is feasible that appropriate frequency assignment criteria could be developed within ICAO that would prevent interference with the other aviation systems. Red: All other circumstances

D.2.7 Security

Table D–20 illustrates how the security capabilities of a technology were used and mapped into the evaluation colors.

TABLE D–20.—SECURITY CAPABILITIES

Security
[G, Y, or R status is assigned based upon the extent to which candidate supports authentication and integrity]. **<u>Assessed as:</u>** Green: candidate supports A&I Yellow: candidate can be modified to support A&I. Red: candidate cannot be modified to support A&I.

D.2.8 Transition

Table D–21 illustrates how the ability of a technology to accommodate transition was used and mapped into the evaluation colors.

TABLE D–21.—TRANSITION

Transition
The candidate must have acceptable transition characteristics, including: • return on partial investment • ease of technical migration (spectral, physical) • ease of operational migration (air and ground users) **<u>Assessed as:</u>** Green candidate: • provides return on investment (i.e. service provision / benefit) without requiring full/complete investment /deployment, and • can be operated simultaneously (in adjacent airspace) with legacy A/G comm. system (i.e. you can bring the new system up incrementally, while bringing the legacy system down incrementally), and • initial transition can be nearly operationally transparent (i.e. initially, users do not have to significantly alter procedures) or features that drive changes in operational procedures can be employed incrementally Yellow candidate: can have no attributes of a Red candidate Red candidate: • provides little or no return on investment (i.e. service provision / benefit) until full/complete investment /deployment, or • requires operation of legacy A/G comm. system be widely discontinued in order to operate, or • initial transition requires significant changes to operational procedures.

APPENDIX E. DETAILED TECHNOLOGY INVESTIGATIONS

A detailed technology investigation has been conducted or is being planned for all technologies brought forward from the technology screening. This ensures a thorough understanding of the behavior of each screened technology in the context of the environment in which it will operate. As some of the behavior (e.g., physical layer performance) is dependent on the spectrum band in which the technologies will operate, detailed technology investigations are organized along applicable spectrum categories. Studied technologies include:

- VHF-Band: None
- L-Band: P34, LDL, WCDMA, B-VHF (at L-Band), L-Band E-TDMA
- Satellite: Inmarsat SBB, Iridium, Custom Satellite Solution
- C-Band: 802.16e

As noted above, no technologies were brought forward from the technology screening process for consideration in the VHF Band. As a result, no discussion specific to this band is provided. Although a full investigation of all aspects associated with each technology may be desirable, time and resource limitations prompted a different approach. Specifically, consideration was given to each technology to determine the most pressing issues requiring evaluation for determining if the candidate is a viable solution. For some technologies, this included evaluation of BER performance in the associated propagation environment and interference issues; for other technologies, functional capability and ability to meet COCR performance requirements was identified as requiring detailed investigation. As a result, the treatment of the technologies in the studies below varies. To accommodate this approach, within each subsection addressing a specific spectrum band, each candidate technology within the band is introduced along with the applicable topic(s) of investigation. The subsequent subsections then provide documentation of investigation results.

It should be noted that at the present time, not all of the technologies emerging from the screening have undergone a detailed investigation. These are indicated by "To Be Performed" and will be addressed during the third and final component of the Future Communication Study technology evaluation (2006 to 2007).

The material in this appendix is organized into the following sections:

- L-Band Environment and Applicable Technology Analysis—Section E.1
- Satellite Environment and Applicable Technology Analysis—Section E.2
- C-Band Environment and Applicable Technology Analysis—Section E.3

E.1 L-Band Environment and Applicable Technology Analysis

Consideration is being given to the use of L-Band (960 to 1024 MHz) to employ the next-generation aeronautical communication system. Several technologies are being considered for this band, including P34, LDL, WCDMA, B-VHF (at L-Band), and L-Band E-TDMA. Upon review of the technology definitions and developed concept of use, technology characterization and/or performance for detailed investigation was identified. The selected analysis topic(s) for each technology was made based on the need to assess those components of the technology that provide the most challenge for application of the technology as a viable solution for aeronautical communication. Selected analysis topics for the candidate L-Band technologies include:

- P34: Protocol model developed in OPNET to assess P34 net entry and data transfer performance; BER performance in the L-Band channel and interference to existing L-Band radionavigation systems

- LDL: BER performance in the L-Band channel and interference to existing L-Band radionavigation systems
- W-CDMA: To be performed (2006 to 2007)
- B-VHF (at L-Band): To be performed (2006 to 2007)
- L-Band E-TDMA: To be performed (2006 to 2007)

For the first two candidates, performance in the anticipated L-Band aeronautical channels was identified as an analysis topic. To perform this work and to assess the viability of proposed communication systems in this frequency band, the multipath dispersion behavior of the aeronautical air-ground channel at L-Band required characterization. While extensive research has been conducted for the land-mobile and the satellite channels at L-Band, very little research has been conducted for the aeronautical air-ground channel.

Thus, prior to assessment of P34 and LDL performance, work was performed to describe a methodology for characterizing the aeronautical air-ground channel at L-Band (960 to 1024 MHz). Included in this work (provided in section E.1.1) is a description of the MATLAB® (The Mathworks, Inc.) simulation used to estimate the propagation effects of the channel. Representative output data is presented and data reduction techniques are also described. Section E.1.1 concludes with suggested channel models for the aeronautical air-ground channel in L-Band. This suggested channel model is used to support the development of a viable concept of operation for candidate technologies for implementation in the L-Band and to support the evaluation of technologies to meet communication performance requirements as captured in evaluation criteria and associated metrics.

Following the propagation environment definition, performance assessments of P34 and LDL in the aeronautical channel are presented in sections E.1.2 and E.1.3 respectively. Interference performance for P34 and LDL are addressed together in section E.1.4. Placeholders are provided for detailed analyses of W-CDMA, B-VHF (at L-Band), and L-Band E-TDMA (in sections E.1.5 through E.1.7). These technologies will be analyzed in the final study component of the Future Communication Study (FCS 2006 to 2007). As viability of an L-Band system was raised as an issue during FCS roadmap development, due to ground infrastructure cost constraints, an economic feasibility assessment for an L-Band FRS ground infrastructure was performed. Results of this work are in section E.1.8.

E.1.1 L-Band Propagation Environment

E.1.1.1 Background

Propagation models are typically classified as either large-scale propagation models or small-scale fading models. Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver separation distance facilitate estimation of radio coverage areas and are referred to as large-scale propagation models. The physical phenomenon they are intended to model is the slow change in average received power with increasing distance from the transmitter. These models are useful for link budgets and coverage analysis. Propagation models that characterize the rapid fluctuations of the received signal strength over very short distances or short time durations are referred to as small-scale fading models. They are characterized by rapid and severe changes in received signal amplitude (several orders of magnitude) with motion over very short distances. The physical phenomenon that they are intended to model is the multipath characteristics of the mobile communications channel. Small-scale fading models are the focus of this study.

Small-scale fading models can be classified as either “frequency-selective” or “frequency-nonselective” (also called *flat*) fading models. Both frequency-selective and frequency-nonselective fading degrade system performance. Frequency-selective fading results in irreducible bit-error-rates (BERs), but these effects can be mitigated by implementing adaptive equalization, spread spectrum techniques, OFDM, or insertion of pilot signals. Frequency-nonselective fading results in destructive interference due to phase differences in the irresolvable multipath components. The effects of flat-fading are generally mitigated by diversity and error-correction coding.

After an extensive literature search, it was concluded that very little measured data exists to characterize the fading behavior of the L-Band air/ground communications channel. Characterization of the Delay Spread and the Doppler Power Spectrum is essential to generating a useful model for waveform simulation and evaluation of candidate Future Radio System (FRS) technologies.

E.1.1.2 Study Approach

In order to form estimates of the delay spread and delay spread statistics, a ray-tracing simulation was developed. The ray-tracing simulation models both diffuse and specular reflections from the Earth's surface. Initially a flat terrain model for the Earth's surface was used, but after the initial investigation it was concluded that mountainous terrain provides a worst-case scenario.

Mountainous terrain, in the en route case, has the potential to provide extremely long multipath delays. Long delay spreads either limit the data rate that can be transmitted or require special techniques to achieve required performance. In an effort to characterize a worst-case scenario for multipath delay spread, Aspen, CO, was selected to be modeled. Figure E–1 illustrates the topography of the Aspen, CO, region.

Terrain elevation data for the Aspen, CO, region was downloaded from the United States Geological Survey (USGS) Web site and imported into the MATLAB workspace. Next, the transmitter and the receiver locations were defined. At this point, a line-of-sight (LOS) visibility check was performed for both the transmitter and receiver. If either the transmitter or the receiver was not in view of a particular point on the terrain, then the terrain, at that point, could not contribute to multipath. Since the transmitter and receiver did not normally fall on top of a point in the terrain, the LOS check used a four-post interpolation method to achieve high accuracy.

The simulation used a method of concentric oblate spheroids to model multipath contributions. Using the transmitter and receiver as focal points, a series of oblate spheroids was generated in the three-dimensional simulation space. The first oblate spheroid in the series was generated so that it just barely intersected the underlying terrain. The semi-minor axis of each successive oblate spheroid was increased by a fixed increment so that the spheroids intersected more and more of the underlying terrain as they were stepped through. The desired product was the set of points on the terrain that were intersected by the oblate spheroids. When plotted, each set of intersection points appears as a distorted annulus approximating the cross section of the spheroid when sliced by the Earth's surface. Each set of intersection points is mutually exclusive from any other set because any intersection point can only be accounted for once. Each set of intersection points contributes to multipath for a particular delay. Figure E–2 illustrates the method of concentric oblate spheroids.

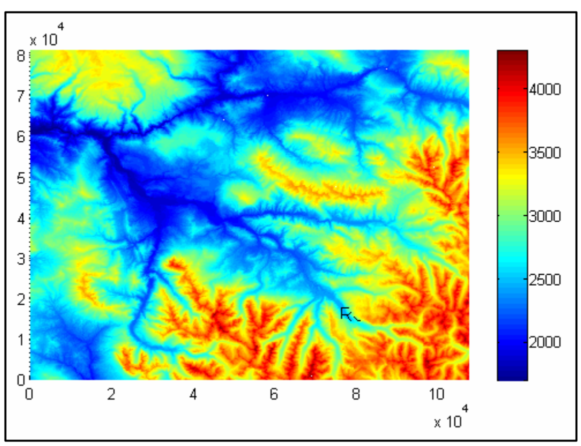


Figure E–1.—Aspen Topography (Elevation in Meters).

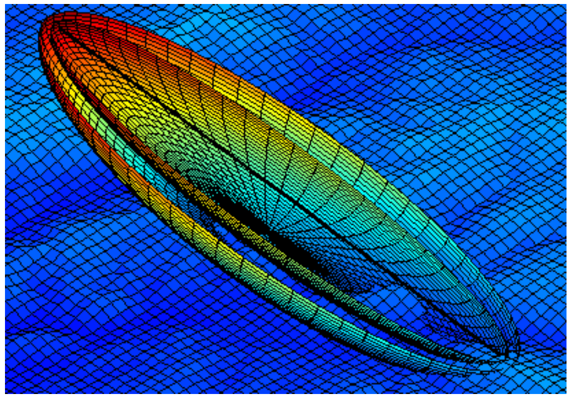


Figure E–2.—Two Concentric Oblate Spheroids Intersecting the Underlying Terrain.

After the simulation determined the sets of intersection points for each spheroid, it was determined whether the individual points would contribute to multipath as either a specular reflection or as a contributor to scattering. If the azimuthal and elevation angles of incidence and reflection were within some small tolerance, chosen as a concession to the granularity of the underlying terrain data, then the amplitude and phase of the ground-reflected wave were calculated using the following equation:

$$\rho_v = \frac{(\varepsilon_r - jx)\sin\psi - \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}{(\varepsilon_r - jx)\sin\psi + \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}$$

where,

- ψ is the elevation angle of the incident wave
- ε_r is the dielectric constant of the reflective surface
- x is a function of both the conductivity and frequency

The power of the specular component was calculated using the free space path loss model in conjunction with the reflection coefficient, $|\rho_v|$. The phase of the ground-reflected wave is a function of the distance traveled, the frequency, and the phase change due to reflection, $\angle\rho_v$.

If an intersection point does not meet the conditions for specular reflectivity, then the point contributes as a scattering surface. All such points for a single oblate spheroid, are clustered together so as to form a larger scattering surface. A majority of the new intersection points end up contributing to multipath this way due to the stringent requirements for specular reflectivity. The methodology for calculating the power of these scatterers was that of the bistatic radar equation (Driessen):

$$L(t) = \frac{\lambda^2}{(4\pi)^3}\frac{\sigma^0 A}{r_{TS}^2 r_{SR}^2}$$

where,

- λ is the wavelength of the communication signal
- σ^0 is the normalized scattering cross section
- A is the area of the mountain slope
- r_{TS} and r_{SR} are the distances from the transmitter to the scattering surface and from the scattering surface to the receiver.

Measurements for σ^0 can be found in the literature and range from about –7 to –21 dB (Driessen). The -7 dB estimate is generally attributed to rocky, barren mountain slopes or sides of buildings. The –21 dB estimate relates to tree-covered landscapes, because they absorb more of the communication signal. The Rocky Mountains contain both types of regions: rocky and forested-covered slopes, but also possess a natural line of demarcation between these types: the alpine tree line. The alpine tree line is the highest elevation at which trees can grow on mountains. Above the tree line, the elements are too harsh to sustain vegetation. This is not to say that rocky slopes do not exist below the tree line, but the tree line gives a first-order approximation for differentiation between landscape types. In the simulation, the bistatic radar equation was applied to areas above the tree line using one value for σ^0, and was also applied to areas below the tree line using another value for σ^0.

An agglomerative clustering algorithm was used to group points together. The clustering algorithm works as follows. A distance matrix is generated that calculates the distance from each point to every other point. The two points separated by the minimum distance are clustered together and then removed from consideration. The next two points that are separated by the next minimum distance are then joined and so on. This process repeats until there are no more points represented in the distance matrix. If there were an odd number of points to begin with, the odd point out remains its own cluster. This entire process is repeated until the desired number of clusters is achieved or some other criteria is met. This algorithm results in the formation of several contiguous clusters, each with areas on the order of those found in the literature (~1 km^2).

The values, or legs, used for r_{TS} and r_{SR} in the bistatic radar equation are critical to properly estimating the scattering loss. Instances where $r_{TS} = r_{SR}$ result in far less power compared to when $r_{TS} >> r_{SR}$ or $r_{TS} << r_{SR}$. An attempt to calculate these values using the legs of the centroids of the clusters resulted in poor values for r_{TS} and r_{SR} because it is possible for the centroid of a cluster to fall near one of the two focal points. Another method using the history of the most recently joined cluster enabled the selection of r_{TS} and r_{SR} values that cannot fall near either of the focal points. The simulation looked back to which two points were used to join the previous two clusters and chose the leg values from one of those two points. That covers all of the variables needed to calculate the power in the bistatic radar equation. The phase of each scattered multipath component was randomly chosen from a uniform distribution from $[0 \ldots 2\pi]$.

For each oblate spheroid, a set of multipath components (specular components, scattered components from above the tree line, and scattered components from below the tree line) was returned. The multipath components were vectorally added for each spheroid. Once all of the powers were calculated, the sum of the powers in the PDP were normalized to be one. The resulting time-delay vector and received power vector formed the PDP.

The simulation allowed the user to define the number of aircraft locations to simulate during a single simulation trial and could return a PDP for each aircraft location. For example, if the user set up a simulation run with 300 aircraft locations, the simulation would return 300 PDPs. This capability allowed the user to collect hundreds of PDPs throughout the Aspen, CO, airspace so that the statistics of the PDPs could be captured.

E.1.1.3 Study Results

The L-Band channel estimator simulation generated hundreds of PDPs. Data reduction techniques were employed to extrapolate channel model parameters from the PDPs. The PDPs generated by the simulation contained multipath components with amplitudes several orders of magnitudes down from the LOS component. If these were true measurements, many of the multipath components would be indistinguishable from the noise floor. The simulation differed from real-world measurements in that it did not have a noise floor. For some PDPs that consisted solely of very low-power multipath returns, a skewing of delay spread statistics was observed in the model. This behavior, while perhaps real, is not likely to be significant due to the nature of our channel (Rician). In other words, although they show up in the model, these low-power returns do not degrade system performance given the presence of a noise floor. A threshold level termed the Minimum Validity Threshold (MVT) was defined to eliminate very low-power multipath returns.

The method for determining the MVT was as follows. Relative frequency plots of the RMS delay spread (pdfs) were generated for a range of MVTs. The literature suggested using a range of 20 to 25 dB for the MVT (Matolak). The pdfs were then fitted to known distributions so that the statistics of the known distributions represented the statistics of the channel for a particular MVT value. Figure E–3 shows a plot of the relative frequency of RMS-DS for each value of MVT.

Theory suggests that the pdf of the RMS delay spread for a Rician channel is exponential. After fitting the pdfs to exponential distributions, the means of the exponential distributions were compared to the means of the sample sets. The mean RMS delay spreads from the known distributions matched closely to the mean of the sample sets so the fit with the least residual error was selected. Figure E–4 shows a plot of the residual error resulting from curve-fitting each relative frequency plot.

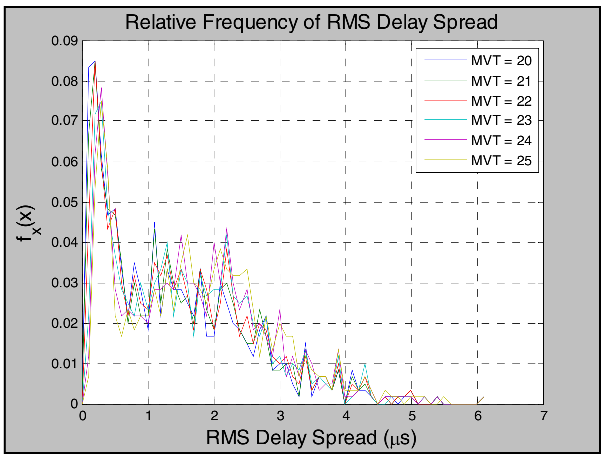


Figure E–3.—Relative Frequency of RMS-DS for Various MVT Values.

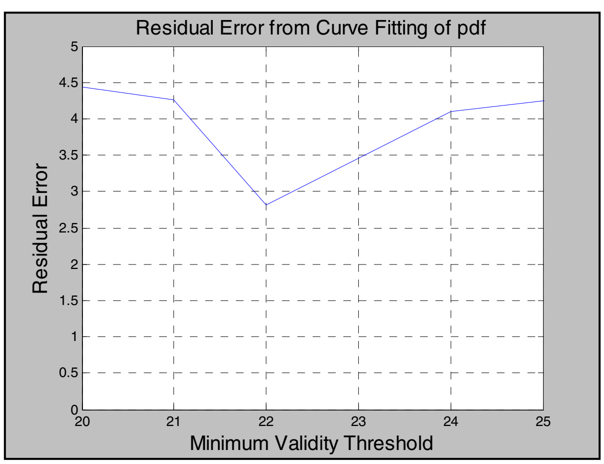


Figure E–4.—Plot of Residual Error From Curve Fitting for Each MVT.

After applying the MVT to all of the PDPs, the mean RMS delay spread was calculated to be 1.4 μs. It is instructive to consider representative technologies at this point since the technology data rate will drive channel model parameter estimation. A rule of thumb that is frequently applied is if the mean RMS delay spread is at least one-tenth of the symbol duration, then the channel is frequency selective (Rappaport 170). In order to illustrate this, two technologies that scored well during the FCS pre-screening were selected for analysis: LDL and P34. Table E–1 shows the corresponding data rates and symbol durations for LDL and P34.

TABLE E–1.—DATA RATES OF LDL AND P34

Waveform	Data Rate	Symbol Duration	1/10th of the Symbol Duration
	R	$T_b = \frac{1}{R}$	$t_0 = T_b / 10$
LDL	62.5 kbps	16 μs	1.6 μs
P34	4.8 kbps*	208.3 μs	20.83 μs

* P34 is an OFDM system. The tabulated data rate is per carrier and is the symbol rate. Overall P34 data rates range from 76.8 – 691.2 kbps

Using our rule of thumb, P34 should undergo flat fading and LDL presents a borderline case because the mean RMS delay spread is very close to one-tenth the symbol duration. It is important to note that frequency-selective channel models differ in structure from flat fading channel models. For this reason it was decided to develop a frequency-nonselective fading model for P34 and a frequency-selective fading model for LDL.

First, the channel model for LDL is described. Figure E–5 shows the block diagram representation for a deterministic simulation model for a frequency-selective mobile radio channel (Pätzold 270).

The parameters that define the LDL channel model are as follows:

- \# of Taps (N)
- Tap Spacing ($a_0, a_1, ..., a_N$)
- Tap Weights ($D_1, D_2, ..., D_N$)
- Tap Fading Processes ($\mu_0, \mu_1, ..., \mu_N$)

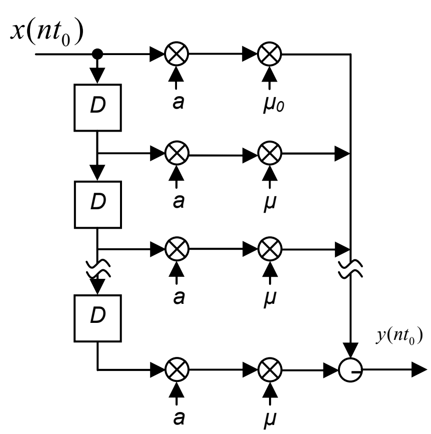


Figure E–5.—Block Diagram for Frequency-Selective Channel Model.

Each of the simulated PDPs contains a large number of multipath components with some being more prominent than others. A good model would emulate the simulated channel without undue complexity. That is, the channel model should require the minimum number of taps required to achieve a good fit. Many researchers (Matolak) use the contribution of a tap to total energy as a barometer of which taps are required. Using this method, one selects the number of taps required to account for X% of the total PDP energy. A selection of X = 99% was used for this threshold. Figure E–6 shows a plot of the cumulative energy per tap. According to this plot, 99% of the total PDP energy is accounted for in the first 7 taps. Therefore, we have chosen the number of taps, N, in the LDL channel model to be 7 taps.

The tap delays should coincide with the sampling of the rate of the physical layer simulation it will be used in. Such simulations require a sampling (typically over-sampling) rate that is an integer multiple of the symbol rate. Aliasing concerns drive typical sampling rates to be on the order of 10 samples per symbol. Hence, for LDL, the tap spacing t_0 = 1.6 μs (LDL symbol duration is 16 μs).

To determine the tap weights we look to a plot of the average energy per tap. Figure E–7 shows the average power of a tap when that tap exists.

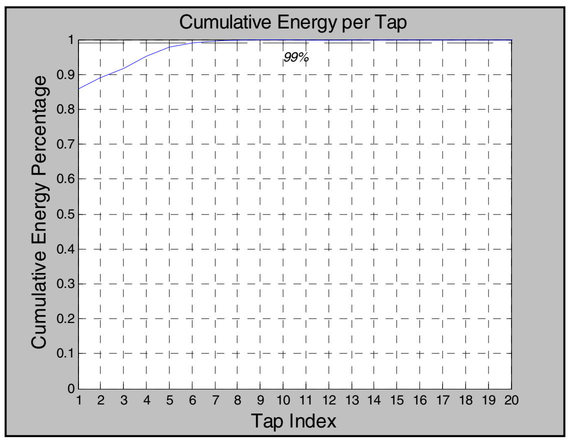


Figure E–6.—Plot of Cumulative Energy Per Tap.

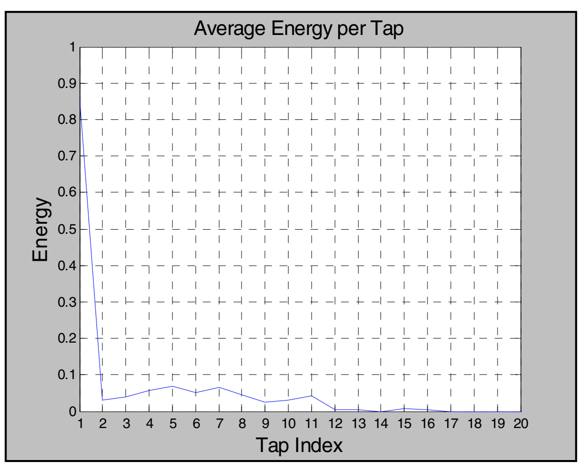


Figure E–7.—Average Energy Per Tap
(When the Tap Exists).

In order to find the fading process associated with each tap we fit the distribution of each tap (when the tap exists) to a known distribution. For all non-LOS taps, the fading process was determined to be Rayleigh. The mean of each Rayleigh distribution should match the mean of the sample space of tap amplitudes. Table E–2 defines the LDL channel model parameters.

TABLE E–2—LDL CHANNEL MODEL PARAMETERS

Tap #	Delay (μs)	Power (lin)	Power (dB)	Fading Process	Doppler Category
1	0	1	0	Rician	Jakes
2	1.6	0.0359	-14.5	Rayleigh	Jakes
3	3.2	0.0451	-13.5	Rayleigh	Jakes
4	4.8	0.0689	-11.6	Rayleigh	Jakes
5	6.4	0.0815	-10.9	Rayleigh	Jakes
6	8.0	0.0594	-12.2	Rayleigh	Jakes
7	9.6	0.0766	-11.2	Rayleigh	Jakes

The P34 channel model is much less complex than the LDL channel model because the channel is frequency nonselective. Figure E–8 illustrates the P34 channel model.

The Ricean fading process is derived in the complex baseband by creating two colored Gaussian processes. The Rice method is used to generate the Gaussian processes as a summation of sinusoids whose coefficients and frequencies are determined by the Doppler Power Spectrum of the channel. As the process is Ricean, a time-variant mean is summed with the colored Gaussian process (LOS component). The magnitude of the complex Gaussian colored processes yields the Ricean process with fade durations and amplitudes determined by the channel.

One of the primary results reported is the simulated RMS delay spread. It should be noted that this delay spread can be modeled as a function of the average distance from the transmitter, with increasing delay spreads reported for increasing distances. Because of this phenomenon, our simulated positions were constrained to be in an area with dimensions that were small compared to the average distance from the transmitter. For these simulations, an RMS delay spread of 1.4 μs was predicted for a certain distance (average distance = 40 miles) from the transmitter in mountainous terrain. A generalized model, using the method cited in Greenstein, has the form:

$$\overline{\sigma}_\tau = \overline{\sigma}_{\tau_0} d^{\varepsilon} A$$

where,

- d is the distance in km
- σ_0 is the median value of the RMS delay spread at d = 1 km
- ε is an exponent that lies between 0.5 to 1.0, based on the terrain type
- A is a lognormal variate

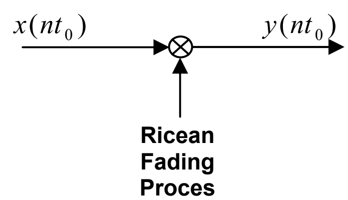


Figure E–8.—P34 Channel Model.

To determine the parameters that are appropriate for a generalized L-Band A/G model in mountainous terrain, RMS delay spreads were predicted for a reference distance of 1 km as well as for the previously mentioned values at 64.37 km (40 miles). The two predicted values that resulted from the simulation work are:

$$\sigma_{RMS}(1\text{ km}) = 0.1\ \mu\text{s}$$
$$\sigma_{RMS}(64.37\text{ km}) = 1.4\ \mu\text{s}$$

Fitting the Greenstein model to the reference data provides a generalized expression for RMS delay spread, which is found to be:

$$\overline{\sigma}_\tau = 0.1 \bullet d^{0.6337} \quad \mu s \quad (A = 6dB)$$

E.1.2 P34 Performance Assessment

P34 has emerged as a candidate technology of strong potential applicability to the future aeronautical communication system. In support of detailed technology evaluations, a detailed assessment of P34 performance has been performed. This assessment included:

- <u>P34 Protocol Stack Evaluation</u>: OPNET modeler was used to generate a high-fidelity simulation of the protocol stack to validate estimated technology performance
- <u>P34 Physical Layer Modeling</u>: a custom C code application was generated to create a high-fidelity P34 physical layer model to provide insight into technology performance in the aviation environment
- <u>P34 Interference Modeling</u>: a model of the P34 transmitter was developed using SPW to assess P34 interference to UAT and Mode S receivers (initially, DME receiver modeling was also undertaken, but was eventually terminated due to lack of “as built” algorithm information and insufficient fidelity with predictions to known results)

The material in this section provides an overview of the P34 technology in section E.1.2.1, then provides details of P34 protocol stack evaluation and physical layer modeling in sections E.1.2.2 and E.1.2.3, respectively. Interference modeling for P34 is addressed in section E.1.4.

E.1.2.1 Overview of P34

APCO Project 34 is an EIA/TIA standardized system for provision of packet data services in an interoperable dispatch-oriented topology for public safety service providers. The concept arose as part of a government/commercial partnership to investigate the provision of universal access to all subscribers across carefully controlled and managed networks for public safety applications. The technology was developed to address “issues that restrict the use of commercial services for mission critical public safety wireless applications,” which include priority access and system restoration; reliability; ubiquitous coverage; and security.

A P34 network, called a Wideband System, can interoperate with other P34 networks, with end-systems, and with mobile users using standardized interfaces. These interfaces, denoted Inter-RF Subsystem Interface (ISSI); wideband RF to end system interface4 (Ew); and wideband RF to mobile user interface (Uw); respectively, are shown in the functional depiction of P34 in figure E–9.

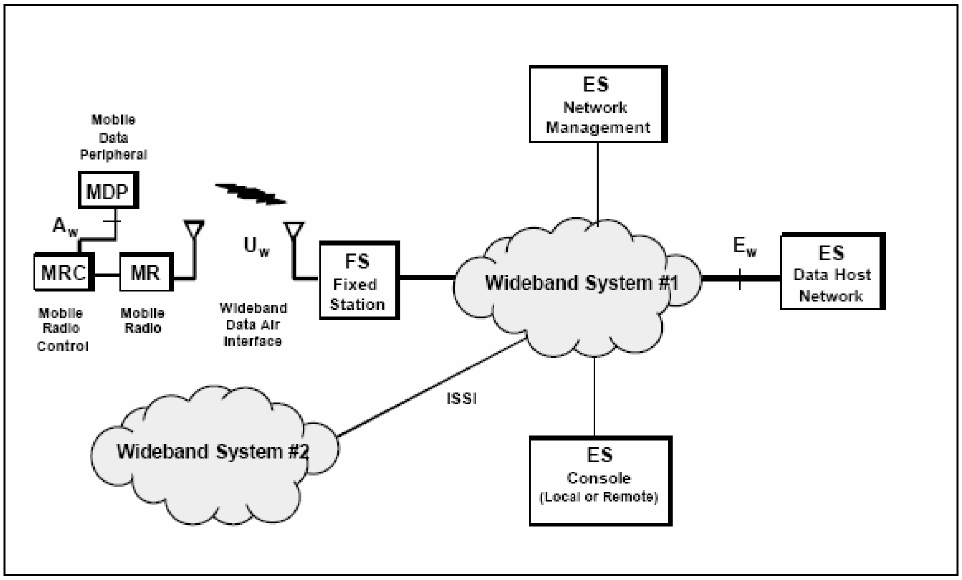


Figure E–9.—P34 Functional Components and Interfaces.

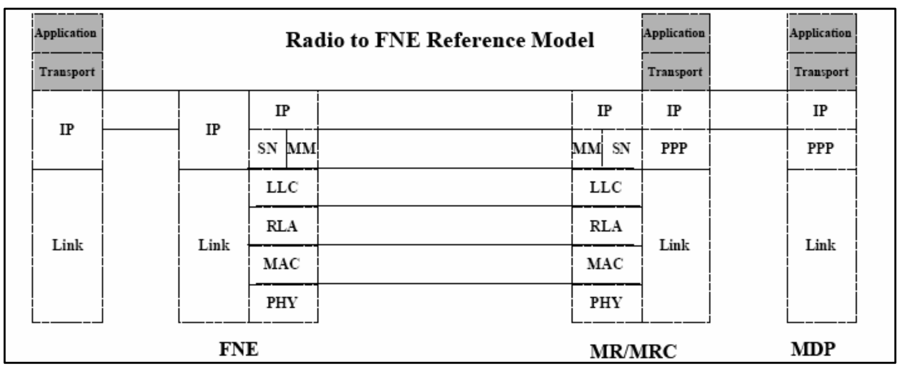


Figure E–10.—P34 Protocol Stack.

The P34 air interface has defined modes between mobiles (mobile radio (MR) to MR); between mobiles and fixed network infrastructure (FNE) and repeated modes for extending communication range to distant stations. As an example of the repeated mode, mobile radios can serve as repeaters to extend the range from the FNE to distant mobile radios.

Shown in figure E–10, the P34 protocol stack is layered, and assumes a point of attachment to an Internet Protocol (IP) network.

Planned P34 system implementations are slated to be deployed using frequency division duplexing with a forward link between 767 and 773 MHz. This forward link provides the FNE to mobile radio connectivity (MRC). The return link, accommodating MRC to FNE, is defined for between 797 and 803 MHz. A depiction of this spectrum assignment, for a TIA-902 P34 system, is provided in figure E–11.

The band identified above is currently used for analog television and is not fully cleared. It is anticipated that it could be cleared by December 31, 2006, in some areas. This date is tied to a number of households with digital-capable television sets. A hard requirement for clearing of the band is January 2009.

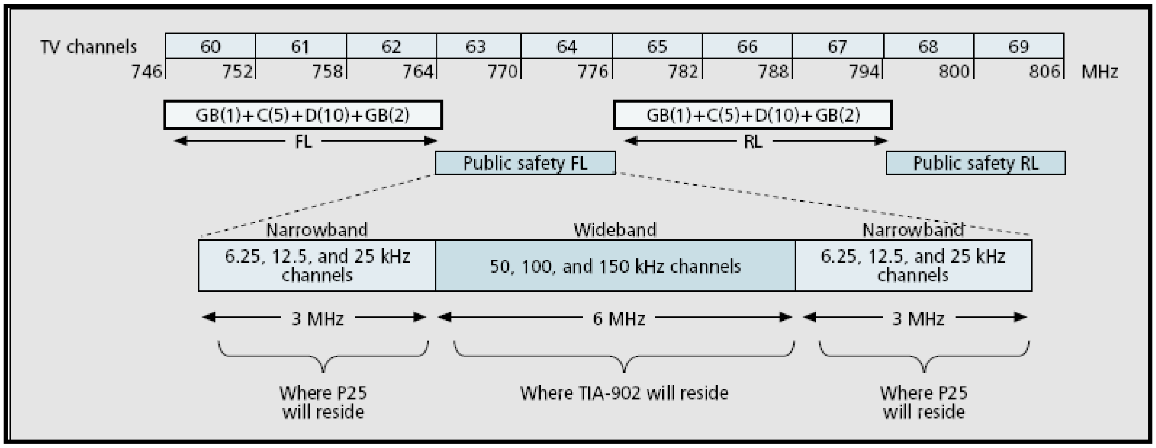


Figure E–11.—P34 Deployment.[134]

E.1.2.2 P34 Potocol Stack Evaluation

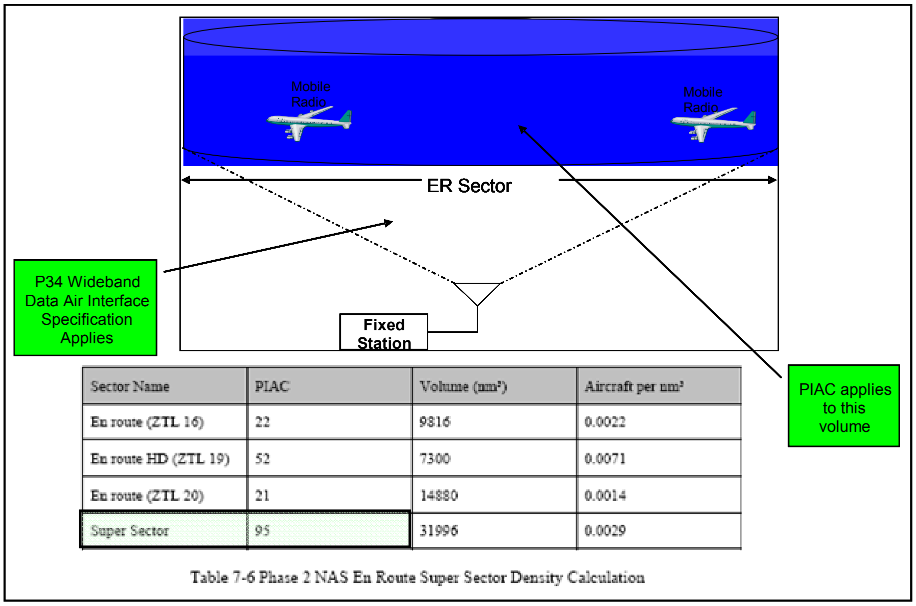
The primary goal of the protocol stack evaluation was to develop a simulation to be used to establish whether P34 meets COCR performance requirements. To evaluate the P34 protocol stack, a simulation context was defined. This included development of an operation scenario, communication nodes, and communication links.

The selected scenario for evaluation was the NAS Super Sector, as defined in the COCR. In this scenario, one fixed station node was used to model the ground station and 95 mobile nodes were used to model aircraft. The defined communication link for this model implemented the P34 Scalable Adaptive Modulation (SAM) air interface. This included 50 kHz channels and QPSK modulation (providing 76.8 kbps). This is the lowest defined P34 data rate, but should be satisfactory for “closing the link” for the sector size defined in the COCR. A depiction of the simulation context for this analysis is shown in figure E–12.

The P34 configuration selected for simulation was the FNE to MR connection, rather than the MR to MR or repeater modes. This modeled configuration aligns with the P34 concept of use defined for applying P34 to the FRS. The custom OPNET development work included the modeling of the P34 Physical (PHY), media access control (MAC), link layer control (LLC), and subnetwork (SN) protocol layers. Figure E–13 identifies in shading the applicable configuration model (base radio (BR) to MR) and modeled layers of the protocol stack.

At the next lower layer of detail, the specific component and functions of the P34 protocol layer addressed in this analysis can be identified. For the subnetwork layer, the protocol dependent subnetwork (PDS)/subnetwork dependent convergence protocol (SNDCP) functions modeled included PDP Context Maintenance (including IP addressing; PDP Context activation; and PDP Context deactivation) and Management of Data Transfers (including LLC UP link maintenance; unicast IP datagrams; MRC-to-FNE SNDCP data transfer; and FNE-to-MRC SNDCP data transfer). The modeled functions of LLC included acknowledged signaling, acknowledged data transfer, and flow control.

For the MAC, logical channel management and synchronization (for the random access channel; slot signaling channel; and packet data channel) and channel access, bandwidth allocation, and contention resolution functions (including priority queuing and slotted aloha reservation requests) were all modeled. Finally, for the physical layer, as indicated previously, the SAM interface was modeled. This included the 50 kHz channel configuration (with 8-RF sub-channels with 5.4-kHz spacing); QPSK modulation with root raised cosine filtering (a = 0.2), 76.8-kbps data rate; and coherent demodulation using pilot symbols.



Sector Name	PIAC	Volume (nm³)	Aircraft per nm³
En route (ZTL 16)	22	9816	0.0022
En route HD (ZTL 19)	52	7300	0.0071
En route (ZTL 20)	21	14880	0.0014
Super Sector	95	31996	0.0029

Table 7-6 Phase 2 NAS En Route Super Sector Density Calculation

Figure E–12.—P34 Simulation Context.

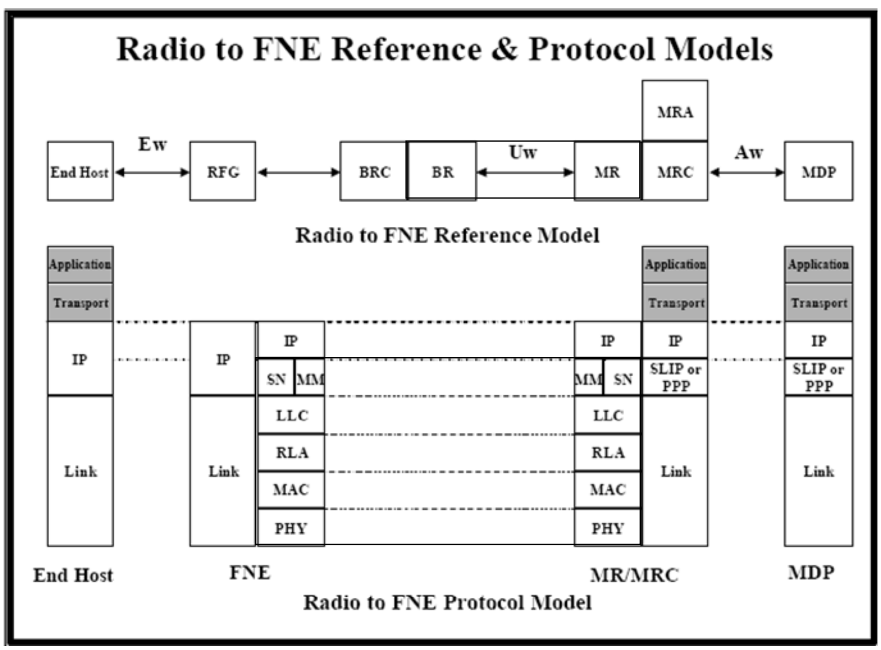


Figure E–13.—Modeled Elements of P34.

To create the simulation data load, the COCR descriptions of aeronautical services, message sizes, and message rates were characterized in OPNET tasks, applications and profile management functions. Specific COCR data utilized for this study included:

- Message sizes
- Suggested classes of service
- Required latencies
- Aircraft count per domain
- Times in service volumes
- Message repetition frequencies

Excerpts of COCR data supporting the OPNET modeling are shown in tables E–3 and E–4.

TABLE E–3.—EXCERPT FROM COCR TABLE 6–12, MESSAGE QUANTITIES AND SIZES

Services	Uplink	Downlink
ACL	4 x 91	4 x 91
ACM	2 x 107	2 x 88
ADS-B	1 x 34	
A-EXEC	1 x 600	1 x 100
AIRSEP	6 x 497	
AMC	1 x 89	0 x 0
ARMAND	1 x 260	1 x 88
C & P	4 x 91	4 x 91
COTRAC (Interactive)	3 x 1969	4 x 1380
COTRAC (Wilco)	2 x 1613	2 x 1380
D-ALERT	1 x 88	1 x 1000
D-ATIS (Arrival)	5 x 100	3 x 93

TABLE E–4.—EXCERPT FROM COCR TABLE 6–9, SERVICE INSTANCES (ATS)—COCR PHASE 2

Service	Type[7]		APT	TMA	ENR
	I	II			
ACL	X	X	Type I&II: 1 (in ground position), both departure and arrival	Type I&II: 2 per sector, both departure and arrival	Type I: 5 per domain Type II: 1 per domain
ACM	X	X	3 per domain (1 in each position), both departure and arrival	1 per sector, both departure and arrival	1 per sector
ADS-B	X	X	Once every 1 s	Once every 3 s	Once every 3 s
A-EXEC** (per service volume)	-	X	0	1 per year per domain	1 per year per domain

E.1.2.2.1 Simulation Models

The simulation model employs a hierarchical structure to describe different aspects of the p34 model to be simulated: the network model, the node model, and the process models. the network model is the highest order in the opnet modeler. it specifies the physical topology of a communications network, which defines the position and interconnection of communicating nodes and links. the specific capabilities of each node are realized in the underlying model. as noted earlier, the simulation evaluation scenario was the nas super sector as described in the cocr. the p34 network model for this scenario is shown in figure e–14. it contains 95 mrc nodes and one fne node. cocr data inputs are characterized in the model’s task, application, and profile configurations.

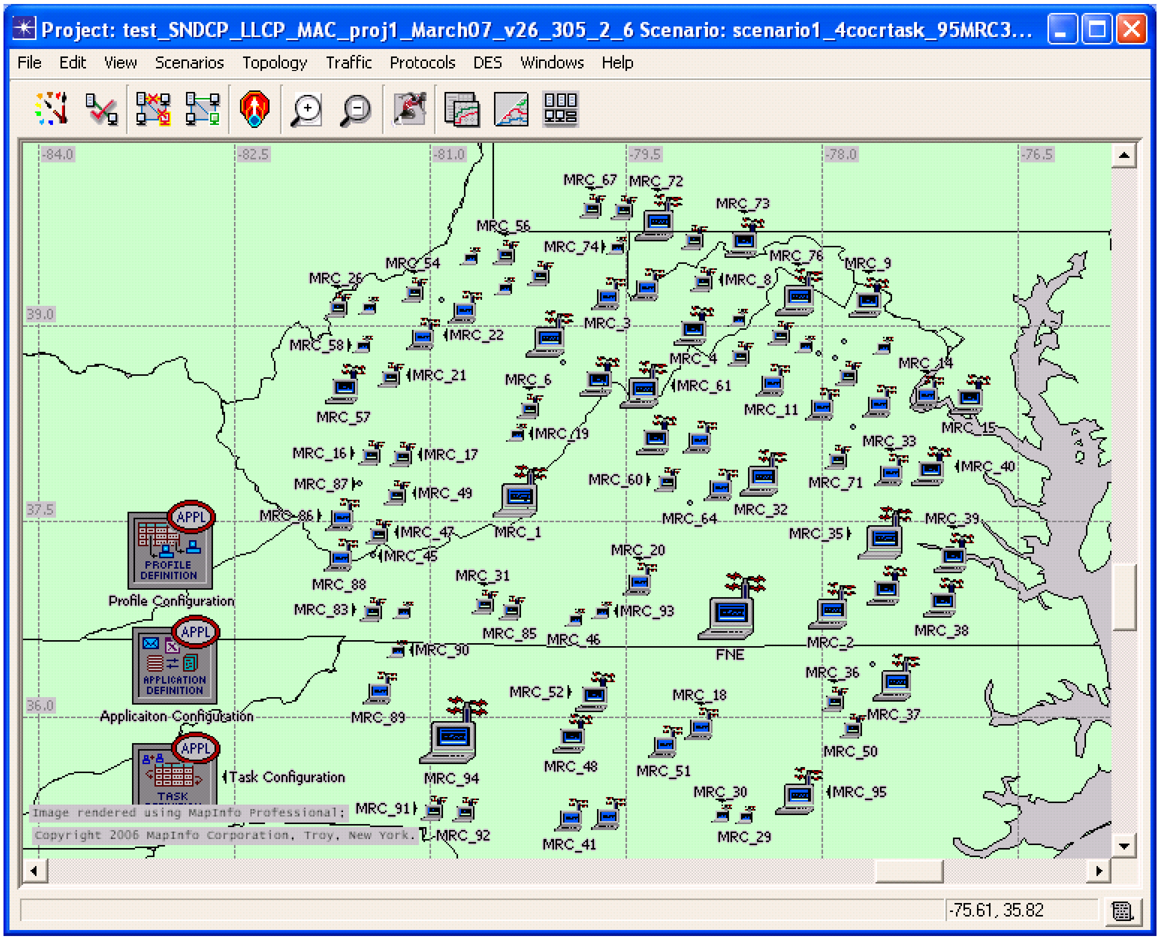


Figure E–14.—The Network Model.

The node model is the second layer in the OPNET hierarchy. Communication devices created and interconnected at the network level are specified in the node model in OPNET. Each node is described by a block structured data flow diagram. Each programmable block in a node model has its functionality defined by a process model. Figure E–15 shows the node model for both MRC and FNE. The IP and upper layer processes are based on the OPNET wireless LAN server node mode; the SNDCP, LLC CP, LLC User Plane (UP), and MAC processes are custom coded. Transmitters and receivers are configured to the assumed P34 physical layer configurations.

The ***process models*** are the lowest level of the OPNET hierarchy. They are used to describe the logic flow and behavior of processor and queue modules. Process models are expressed in a language called Proto-C, which consists of state transition diagrams, a library of kernel procedures, and code programmed in standard C programming language. The defined states of each process model for each of the process model developed in the simulation are presented below. The conditions that make the states transition are programmed in the model and details are not provided in this document.

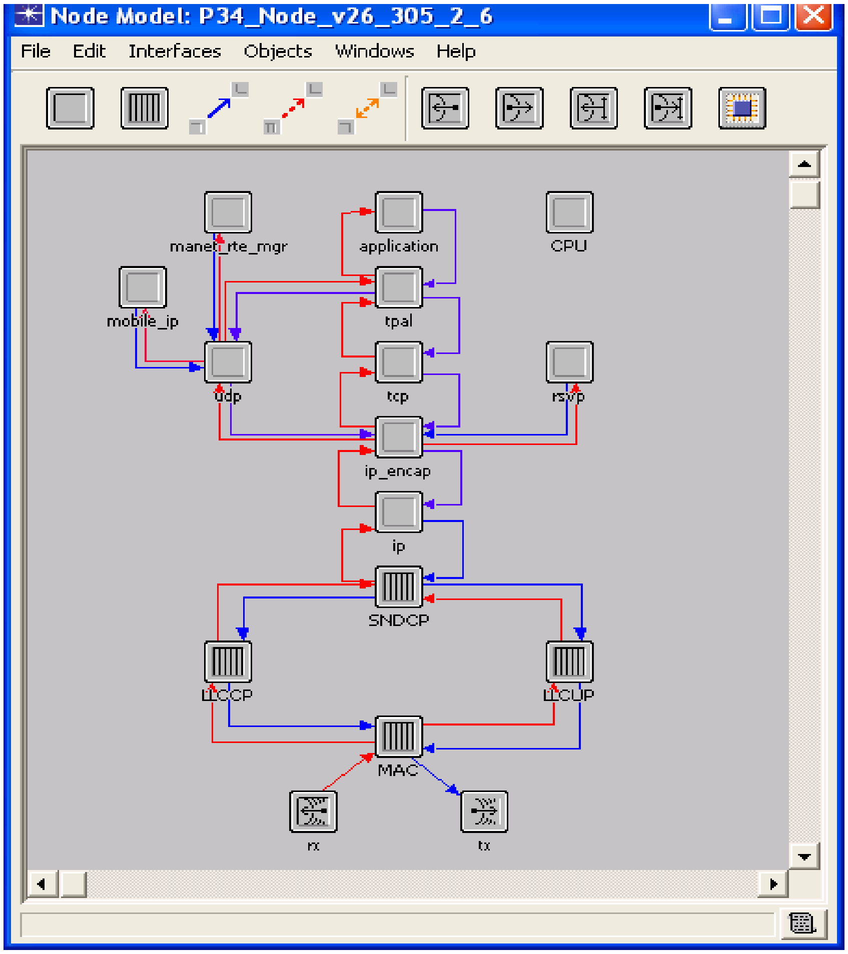


Figure E–15.—The P34 Node Model.

The P34 custom SNDCP process model is shown in figure E–16. Defined states are:

- **Init state—**Initializes setup and variables of the program
- **Idle state—**No context is activated
- **Standby State—**At least one context is activated, but no UP connection yet
- **Ready State—**Exchange data

The P34 custom LLC CP process model is shown in figure E–17. Its defined states are:

- **Init state—**Initializes setup and variables of the program
- **Closed State—**Successful FNE configuration and WAI address (SAC) is allocated
- **Open State—**LLC accepts service requests

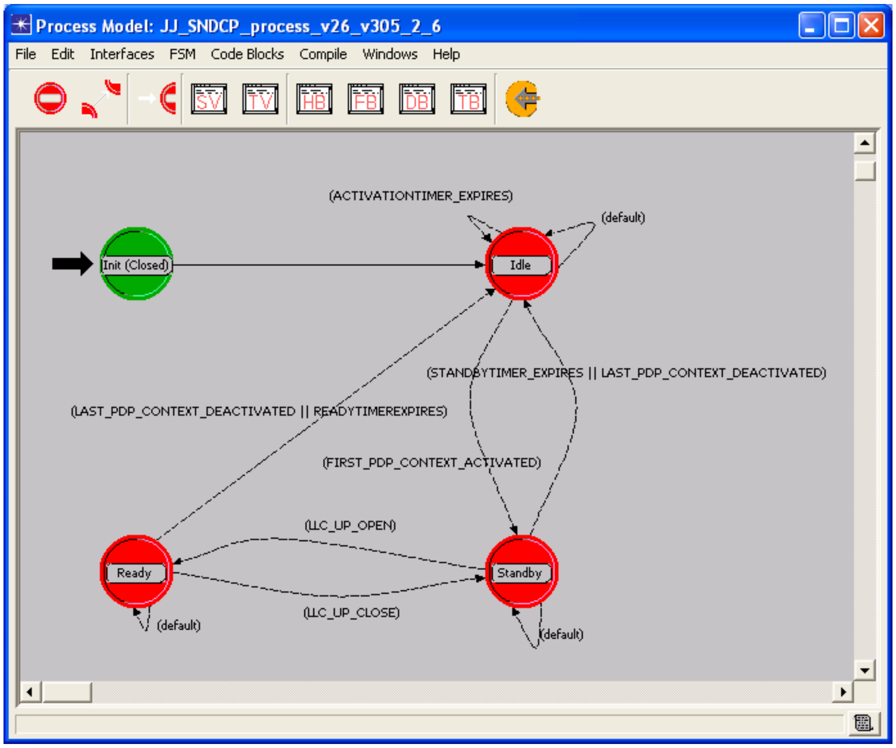


Figure E–16.—P34 SNDCP Process Model.

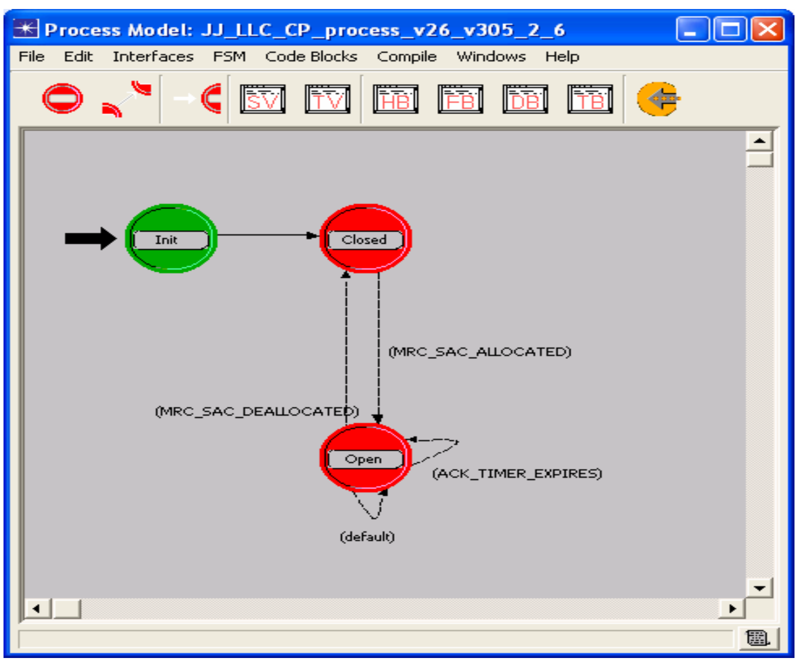


Figure E–17.—LLC CP Process Model.

The P34 custom Link Layer User Plane (LLC UP) process model is shown in figure E–18. Its defined states are:

- **Init state—**Initializes setup and variables of the program
- **Connect State—**Request to set up UP connection
- **Open State—**Accepts user data transmission service requests

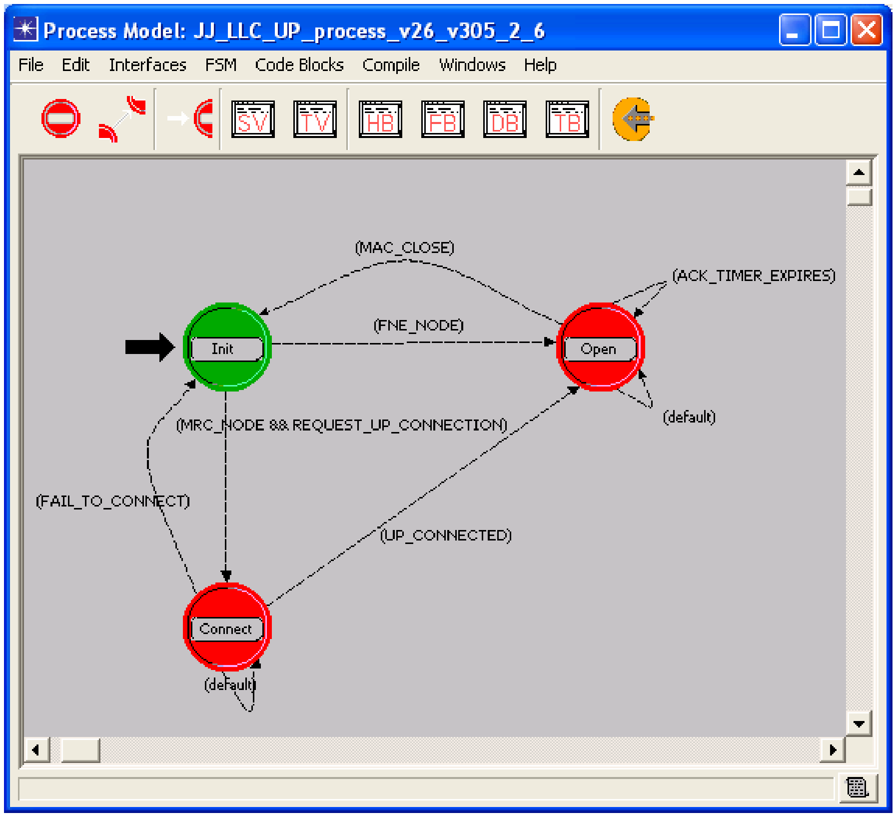


Figure E–18.—LLC UP Process Model.

The P34 custom MAC process model is shown in figure E–19. Its defined states are:

- **Init state—**Initializes setup and variables of the program
- **Idle State—**Accept service requests and decides next processing state
- **Link Management State—**MRC uses RACH to request a SAC
- **MAC_Packet_Process State—**Process incoming MAC packets
- **CP_Packet_Process State—**Process incoming CP packets
- **UP_Packet_Process State—**Process incoming UP packets
- **Resource Allocation State—**Allocate time slots
- **Transmit State—**Transmit packet when time slot is available

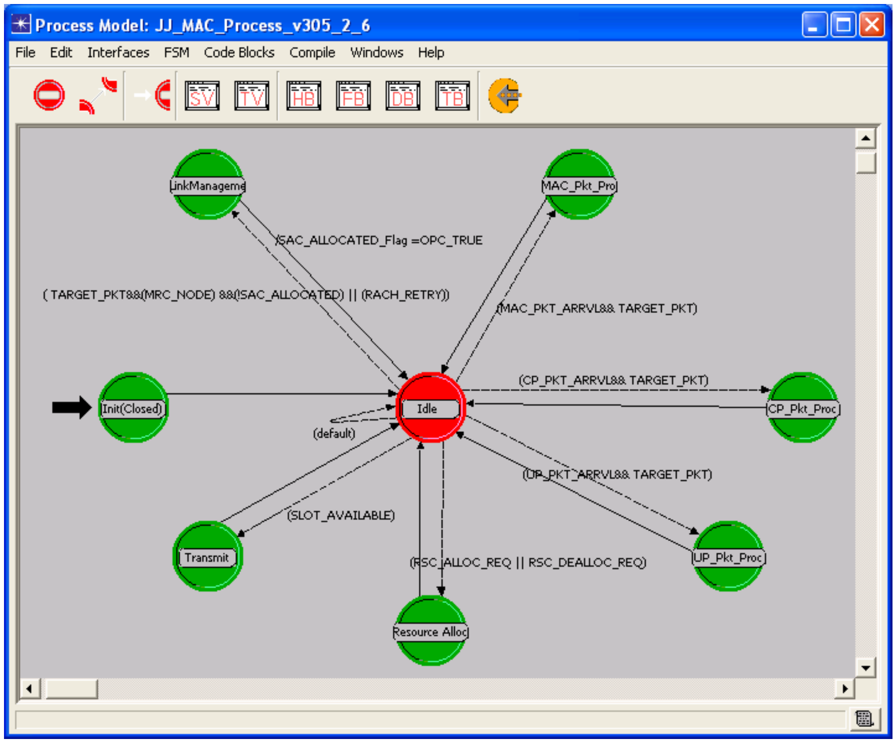


Figure E–19.—MAC Process Model.

E.1.2.2.2 Simulation Results: Traffic Sent

Opnet modeler automatically generates modeled network traffic information and task response time for the simulation model. the custom application traffic (offered load) output is shown in figure e–20. more specifically,

- The traffic load is from 95 airplanes (MRCs) to one ground station (FNE)
- Simulation duration is on the ordinate—simulation duration is 1 hour
- Abscissa is the peak load by traffic class in bytes per second
- Simulation uses same QoS classifications as are suggested in the COCR, four types of traffic loads are configured, network overhead data (highest priority), high priority data, medium priority data, and low priority data, both stacked and individual traffic loads are shown in figure 10.
- Load is not staggered—all 95 aircrafts are assumed in the airspace at the start of the simulation
- There is some startup loading as all of the mobiles attempt context activation

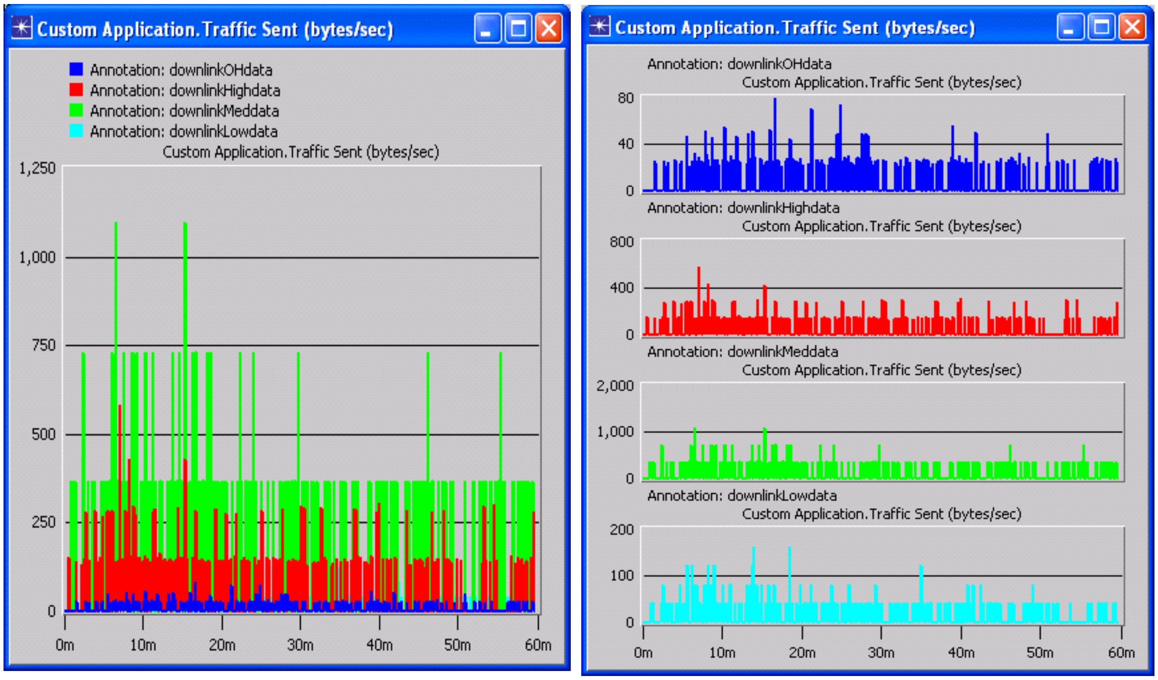


Figure E–20.—Traffic Sent (Bytes/Sec)—95 MRCs.

E.1.2.2.3 Simulation Outputs/Results

Figues E–21 and E–22 show the response time of the P34 simulation to the offered load for each of the transmitted messages. OPNET output indicates that 95% of the sub-network latencies over P34 protocols (SNDCP, LLC CP, LLC UP, and MAC) is under 0.7 seconds. There are some startup outliers due to the initial context activations. These results indicate that the P34 simulation to the offered load meet COCR latency requirements.

E.1.2.2.4 Conclusions

In this task, the P34 simulation model is developed using the OPNET Modeler. Major functions of the P34 SNDCP, LLC CP and UP, and MAC protocols are custom coded and modeled. Physical layer is simplified in this task. COCR data inputs are configured into the model's task, application and profile configuration. One COCR Super Sector of 95 airplanes and one ground station is modeled. Simulation results show that the P34 simulation to the offered load for each of the transmitted messages meet COCR latency requirements.

E.1.2.3 P34 physical layer modeling

The objective of this analysis was to develop a physical layer simulation of P34 and to estimate the performance in the expected propagation environment. The methodology employed included:

- Developing a physical layer model of the technology
- Validating and iterating as required with known results
  - Most standards define the transmitter implementation, but only provide required receiver performance
  - Some iteration of receiver implementations (various algorithms for pilot estimation and the like) was required to achieve required performance
  - In the case of P34, the required performance was specified in the context of a particular channel model

- o This model, a COST207 model, HT200 and TU50, is not applicable to the projected use of the technology, but had to be simulated to verify receiver implementation
- Introducing L-Band channel model and assessing performance
  - – Made modifications to standardized waveform as required to optimize performance

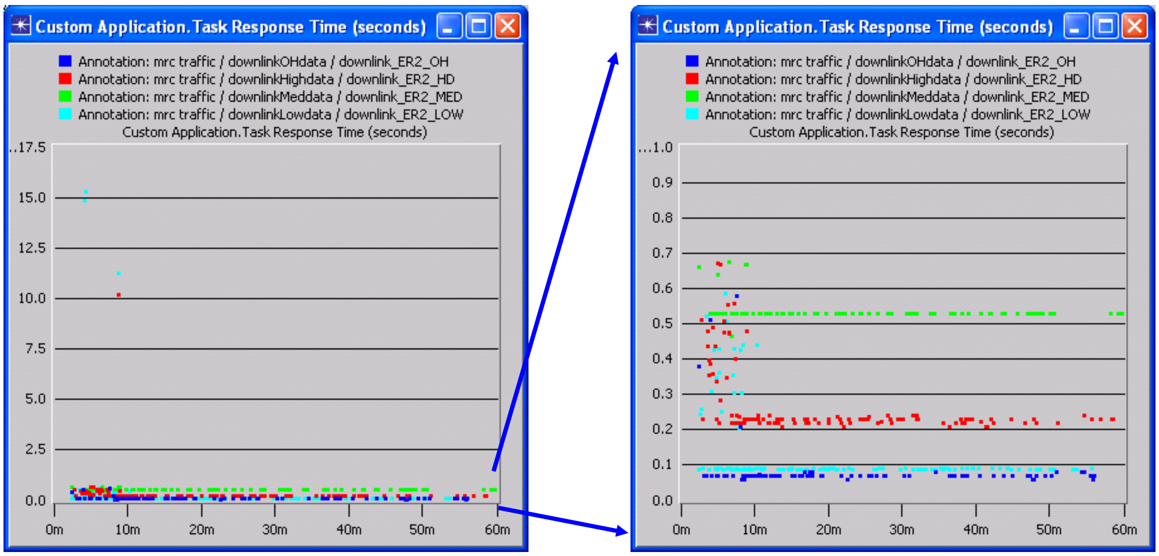


Figure E–21.—Application Response Time.

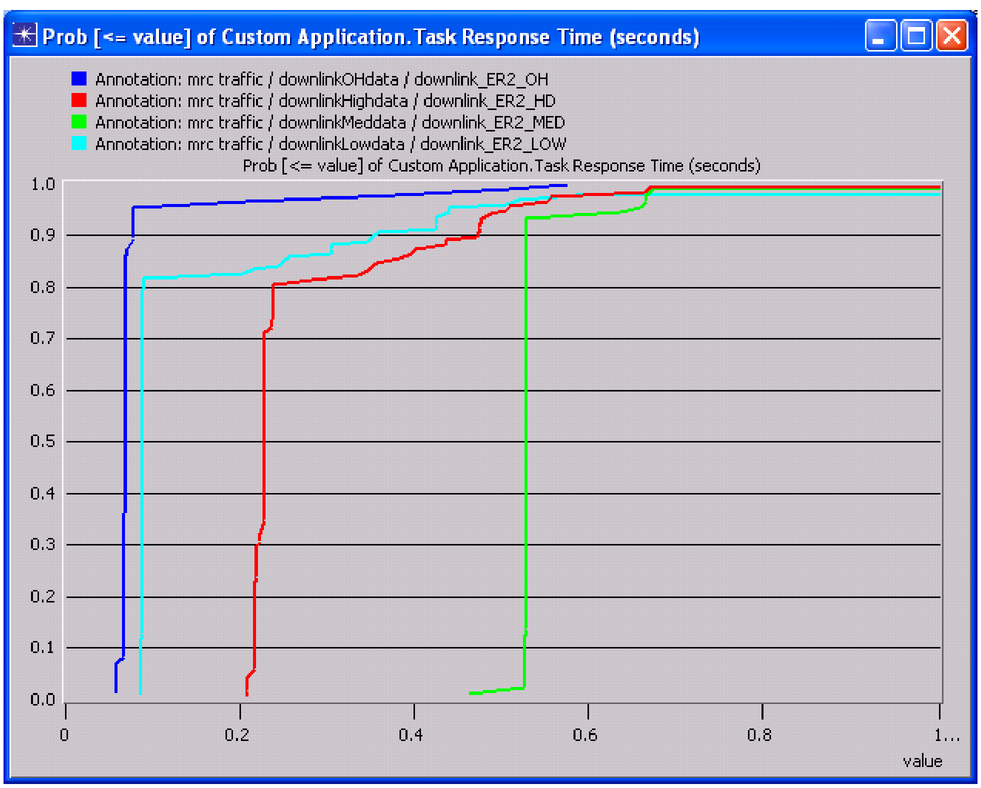


Figure E–22.—Task Response Time (CDF).

A depiction of specific work elements supporting this approach is shown in figure E–23.

The first step supporting the development of transmitter and receiver models was selecting the right analysis tool. Several options were explored for this task. The P34 pilot locations (interspersed throughout the data) made MATLAB Simulink a poor choice as a modeling environment. An example of the complexity required to model P34 in Simulink is shown in figure E–24 (note that this is only a partial model of the P34 receiver).

A second modeling option for P34 using custom C code was evaluated and selected for this analysis. The custom code that replaces all the Simulink complexity shown includes five lines of code, specifically:

```
for (nb = 4; nb < 48; nb+=12)
{baud[nb].symbol[0] = pilotValue;
baud[nb].symbol[2] = pilotValue;
baud[nb].symbol[5] = pilotValue;
baud[nb].symbol[7] = pilotValue;}
```

To perform the P34 analysis, a model of the physical layer was first created. A block diagram of the physical simulation components is shown in figure E–25.

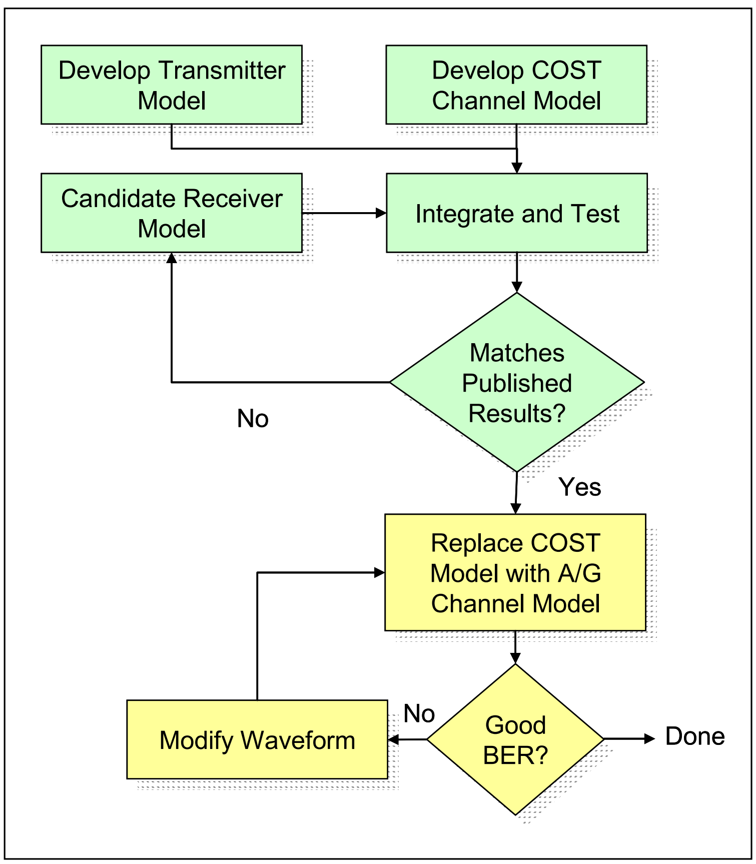


Figure E–23.—Overview of P34 Physical Layer Modeling Approach.

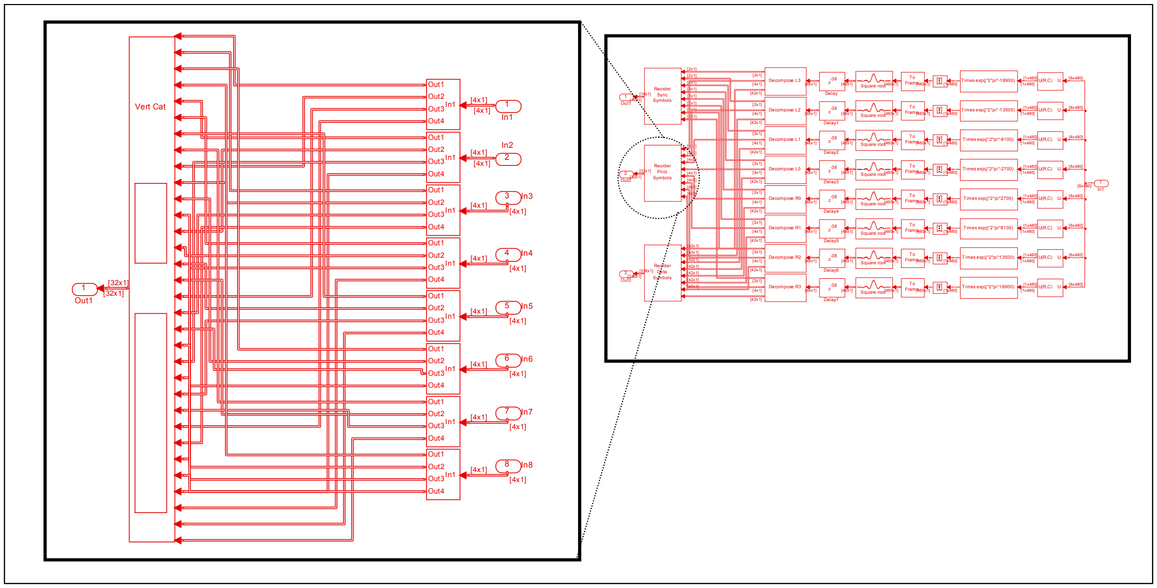


Figure E–24.—Partial Model of P34 Receiver Model in Simulink.

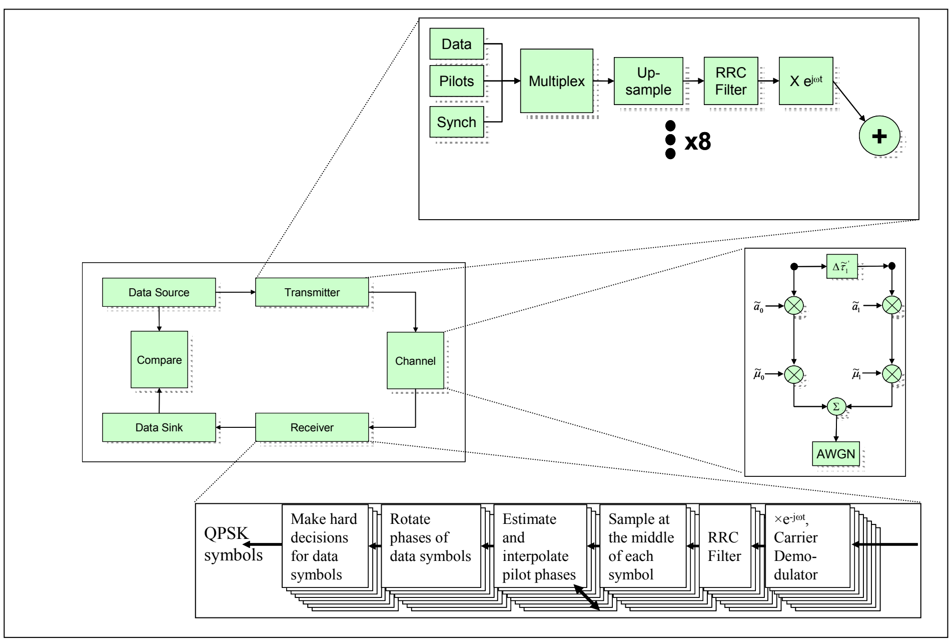


Figure E–25.—P34 Physical Layer Simulation Block Diagram.

Turning next to channel characteristics and their impact on P34, it can be noted that each channel model tap in a Rayleigh channel model is time-correlated. The scale of this correlation is a function of the maximum Doppler speed. If tap fading processes are modeled using the Jakes Doppler spectrum, the autocorrelation function for the impulse response of the channel can be described as a 0^{th}-order Bessel function of the first kind with an argument that is $2\pi f_{max}\tau$. For a standard channel model definition, specifically the HT200 model (200 km/h max. Doppler speed) and operating frequency of 750 MHz, correlation decays over approximately 14 bauds. This channel impulse response is shown in figure E–26.

It should be noted that the time separation between P34 pilot symbols in the same sub-channel is 12 bauds. To apply this information, the use of the P34 pilot symbols for channel estimated is considered. For P34, the phase rotation for a data symbol is computed as a weighted sum of phase rotations for contributing pilot symbols. The contributing pilot symbols are limited to those that are in proximity of the data symbol in time and frequency. A representation of the use of contributing pilot symbols is shown in figure E–27. Note that only pilot symbols within 9 bauds and within 1 sub-channel of the data symbol are used.

Several general rules are applied to assign pilot symbol weights. Specifically, weights are smaller if time separation from the pilot symbol to the data symbol of interest are larger. Additionally, weights are smaller if the pilot symbol amplitude is small. This second rule helps to mitigate the effects of fading.

The channel estimation process described above was used to support the development of P34 transmitter model, and more directly, the P34 receiver model. The P34 Scalable Adaptive Modulation (SAM) physical layer interface was modeled in a custom C code application. The transmitter was implemented as detailed in the specification for the 50-kHz channel using QPSK modulation (note that channel coding and interleaving were not modeled). The receiver was modeled and then tested against published performance results. Specifically, the graphic on the left below in figure E–28 shows P34 performance as published in Annex A of the TIA-902.BAAB-A specification. The graphic on the right shows simulation results for AWGN and the HT200 channel model. Good correlation in results was achieved.

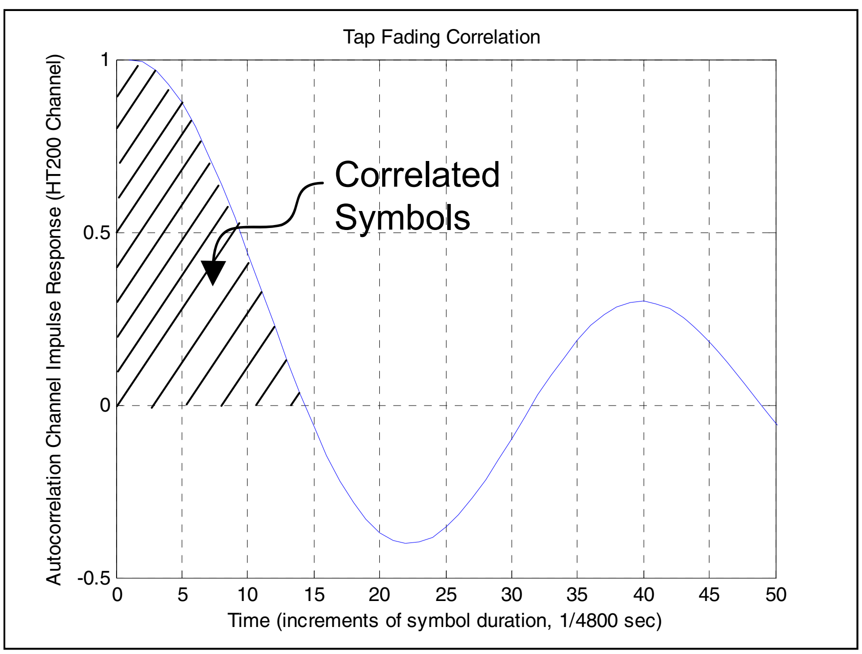


Figure E–26.—HT200 Channel Impulse Response (V=200 kb/Hr, F=750 MHz).

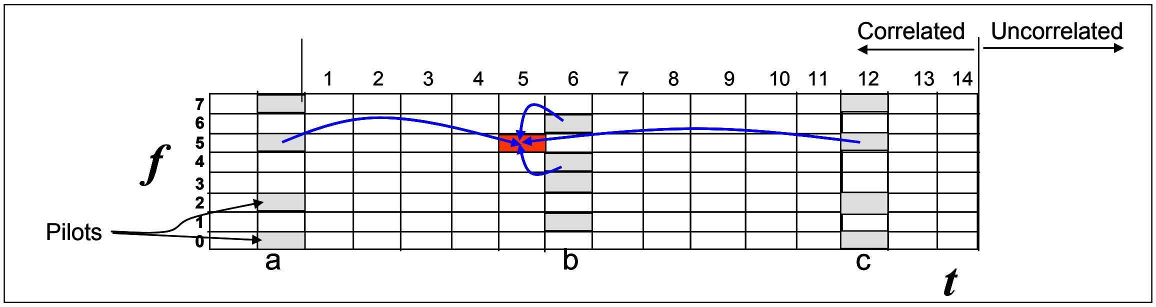


Figure E–27.—Channel Estimation Using Interpolation Weighting.

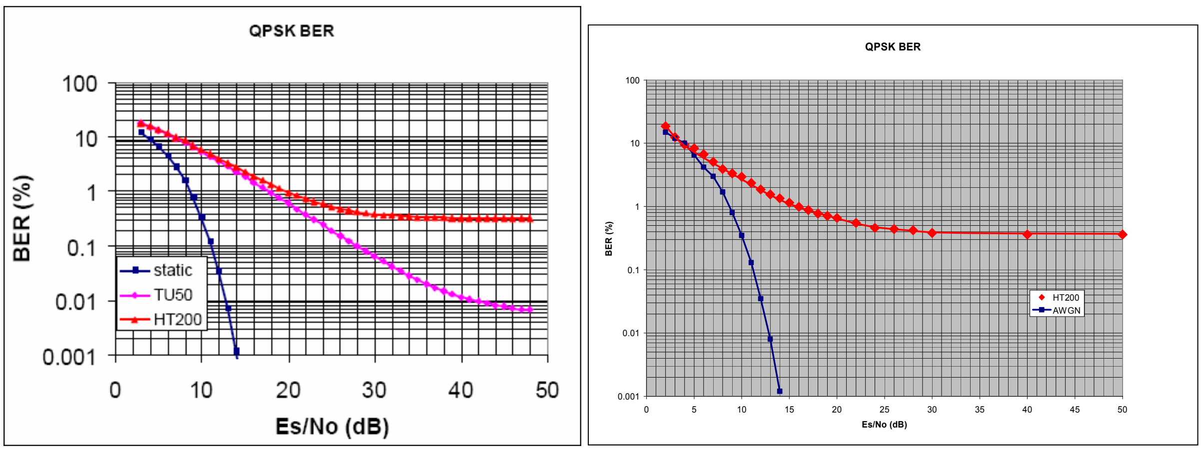


Figure E–28.—Validation of the P34 Receiver Model.

As a point of information, two standard COST models are suggested for evaluation of terrestrial (mobile) communications. The first, TU50, is the COST “Typical Urban” 50 kb/h and is implemented with two taps, both Rayleigh faded (no direct path) where one tap is delayed and attenuated by 5 µs and –22.3 dB. The second model, HT200, is the COST “Hilly Terrain” 200 km/h only, implemented with two taps, both Rayleigh faded (no direct path) where one tap is delayed and attenuated by 15 µs and –8.6 dB. The suggested aeronautical channel model (defined in section E.1.1) might be less severe than the two models noted above. This is because there is no resolvable multipath (in other words, there is flat fading) and there is a dominant LOS component (large K-factor). However, very high Doppler implies that channel coherence time is less than the pilot structure of P34 can support.

From the previous results shown above (for HT200), it was unclear if satisfactory performance was being achieved in the mobile fading channel. Specifically, the need to determine what a raw BER of 3 * 10^{-3} resulted in after coding was identified. P34 SAM uses a system of concatenated Hamming codes, with the basic scheme as depicted in figure E–29.

The rate ½ coding was simulated by concatenating two Hamming coders and a block interleaver. The coding gain is shown in figure E–30. Note that 3 * 10^{-3} BER (referred to later as the “threshold”) is approximately 10^{-5} coded BER.

To model the aeronautical channel model defined in section E.1.1, several changes to the COST model were required. Specifically, the HT200 model was modified to produce Rician statistics. The HT200 channel model changes and resulting simulated channel model are shown in figure E–31 (left and right graphics, respectively).

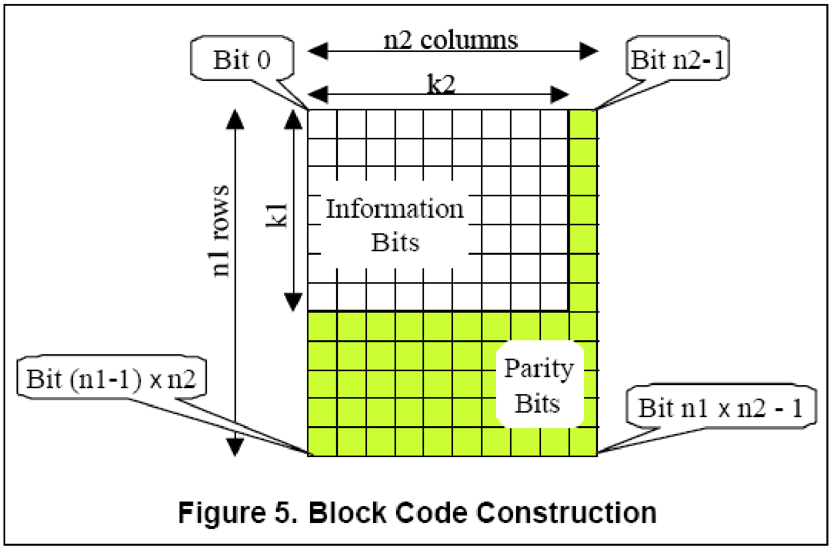


Figure E–29.—P34 SAM Coding Scheme.

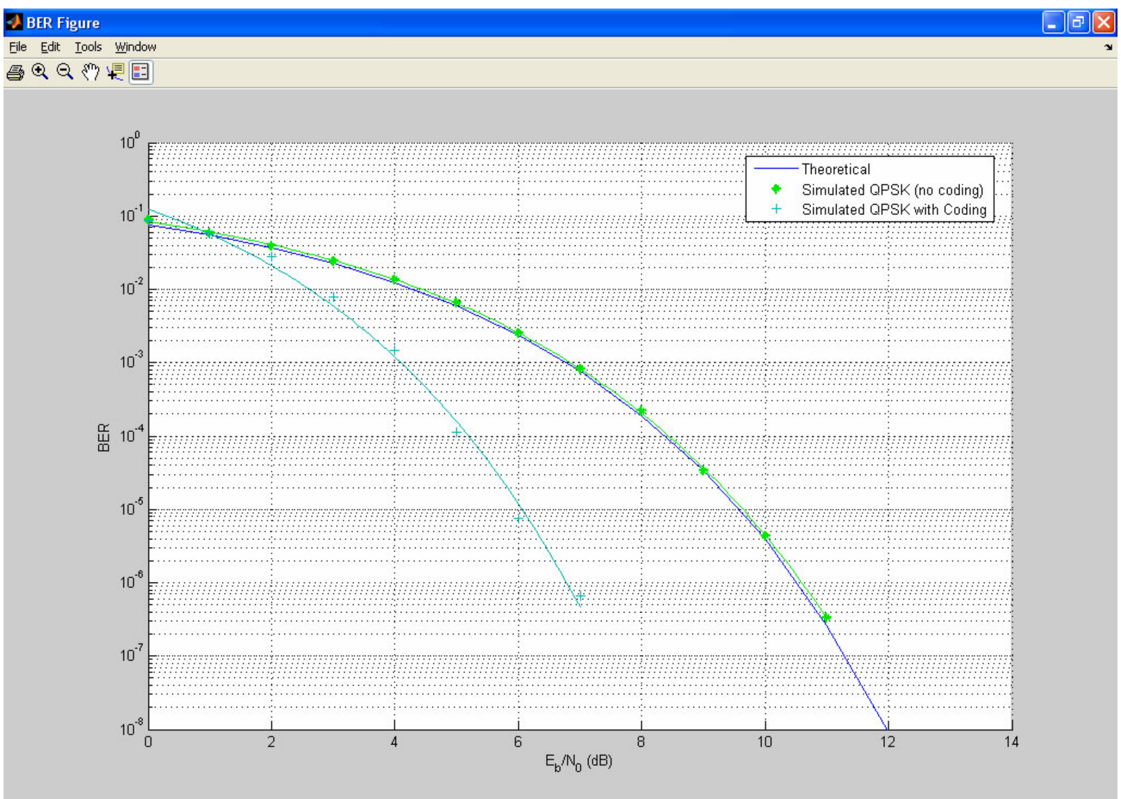


Figure E–30.—P34 SAM Coded BER Performance.

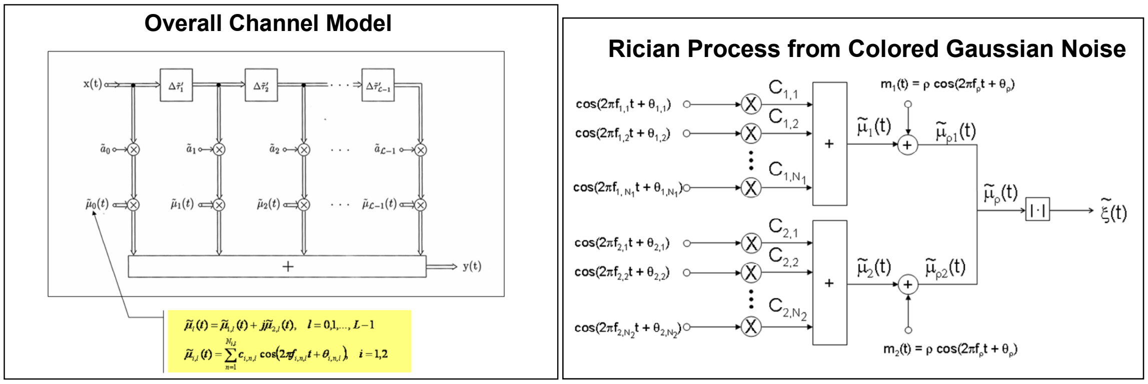


Figure E–31.—Simulated Channel Mode.l[135]

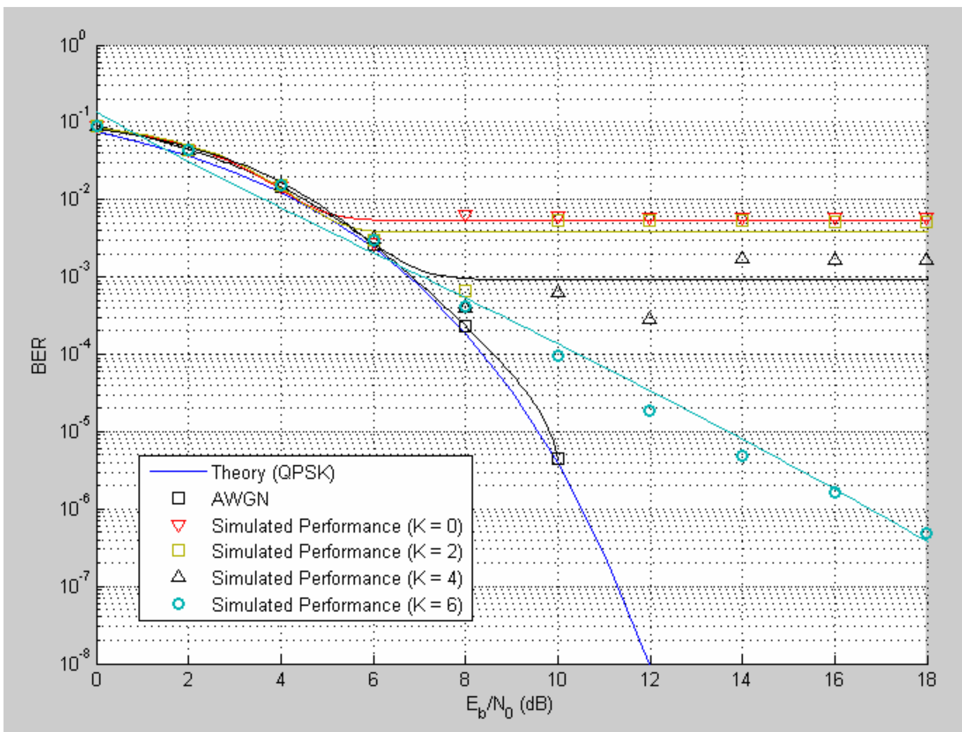


Figure E–32.—Simulated Performance of P34.

The air/ground channel model included two taps. Tap 1 was modeled as Rician with a K-factor of 18 dB, unity gain, and Jakes Doppler spectrum. Tap 2 was modeled as Rayleigh, with a 4.8 µs delay, –18 dB average energy, and Jakes Doppler spectrum. The mobile velocity for the simulation was taken to be 0.88 mach. The COCR identifies this value as the maximum domestic airspeed based on the Boeing 777 maximum airspeed. Additionally, for this model, P34 tuned frequency was taken to be 1024 MHz, with maximum Doppler shift of 1022 Hz.

Combining all simulation components (transmitter, receiver, and channel), simulated performance results for P34 were generated as shown in figure E–32. Initial indications are that P34 performance is expected to be acceptable.

Preliminary conclusions imply that the P34 pilot structure is not robust enough to work in a Rayleigh faded channel at aircraft speeds. However, simulations indicate good performance can be achieved in the aeronautical channel. This is primarily a consequence of the strong LOS component of the received signal.

E.1.3 LDL performance assessment

LDL is another strong candidate technology for applicability to the future aeronautical communication system. To support of technology evaluations, a detailed assessment of LDL physical layer performance has been performed. The material in this section first provides an overview of the LDL technology (section E.1.3.1) and then documents the methodology and results of the physical layer assessment (section E.1.3.2). Similar to the P34 detailed analysis, interference modeling for LDL was also performed, but is documented later in section E.1.4.

E.1.3.1 Overview of LDL

LDL is the VDL3 technology with a redesigned physical layer and slight modifications to the link layer to facilitate operations in L-Band (960 to 1024 MHz). Specific LDL physical layer parameters, in contrast to VDL3 (and also UAT) are shown in table E–5.

TABLE E–5.—LDL KEY PHYSICAL LAYER PARAMETERS

	VDL3	LDL	UAT
Modulation	D8PSK	BFSK	BFSK
Data Rate	31.5 kbps	62.5 kbps	1.041667 Mbps
Synchronization Preamble	16 8-ary symbols	36-bit sequence	36-bit sequence

Modifications to the VDL3 link layer for LDL include the increasing of the defined TDMA guard time, increasing the number of TDMA time slots, and increasing the lengths of various message types.

E.1.3.2 LDL physical layer modeling

The objective of the LDL physical layer modeling task was to develop a simulation of LDL to estimate the performance of the technology in the expected propagation environment. The specific methodology employed for this task included:

- Developing a physical layer model of the technology
- Validating and iterating as required with known results
  - Most standards define the transmitter implementation, but only provide required receiver performance
  - In the case of LDL, the required performance without coding is identical to that of binary CPFSK, which is outlined in many digital communications textbooks
- Introducing L-Band channel model and assessing performance
- Making recommendations for receiver implementation to overcome effects of the L-Band propagation environment

A depiction of specific work elements supporting this approach is shown in figure E–33. These work elements include steps to implement the L-Band channel model in MATLAB Simulink (as defined in section E.1.1); develop an end-to-end simulation model for LDL and validate the model against published theory; integrating the L-Band channel model with the end-to-end simulation; and run the integrated simulation.

The end-to-end physical layer simulation model developed for this analysis consisted of a data source, a transmitter, a channel, a receiver, and a data sink. Graphical representation of this model is provided in figure E–34.

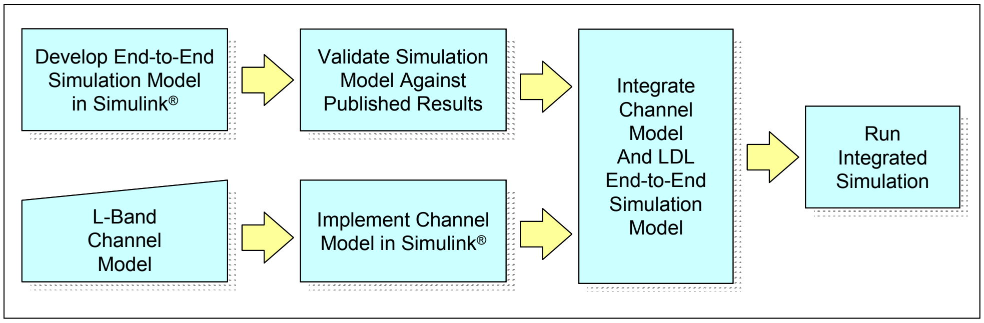


Figure E–33.—Overview of LDL Physical Layer Modeling Approach.

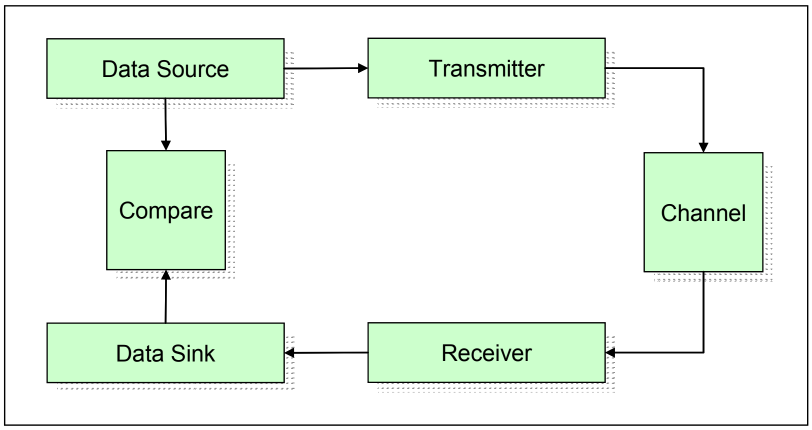


Figure E–34.—LDL End-to-End Physical Layer Simulation Model.

Using the model above, transmitted data is compared with received data and BER computed to assess performance.

LDL uses raised cosine pulse-shaping in conjunction with CPFSK for modulation. To gain insight into the effects of the different aspects of binary CPFSK modulation (i.e., traceback length, pulse length, etc.), the modulator and demodulator were developed as custom models. As an example of implementation details, the binary CPFSK modulator was implemented as a hierarchical model using native Simulink blocks as shown in figure E–35.

The binary CPFSK demodulator was implemented using the "Embedded MATLAB Function" block and native downsample block in Simulink. This supported the decomposing and coding of the CPFSK demodulator in the Embedded MATLAB editor. Demodulator model implementation is shown in figure E–36.

An understanding of the CPFSK demodulator algorithm was required for this simulation. The demodulator uses the history of all previously demodulated symbols up to the current time and appends the sequence with all possible length-n permutations of future symbols. This results in 2^n possible sequences for binary symbols (M^n for M-ary). Next, each sequence is cross correlated with the received signal. The middle symbol of the appended sequence with the highest cross-correlation value is chosen as the demodulated symbol. A full discussion of the demodulator algorithm can be found in section 5.3.3 of Proakis' book Digital Communications.[136] A block diagram of the demodulator for detection of CPFSK is shown in figure E–37.

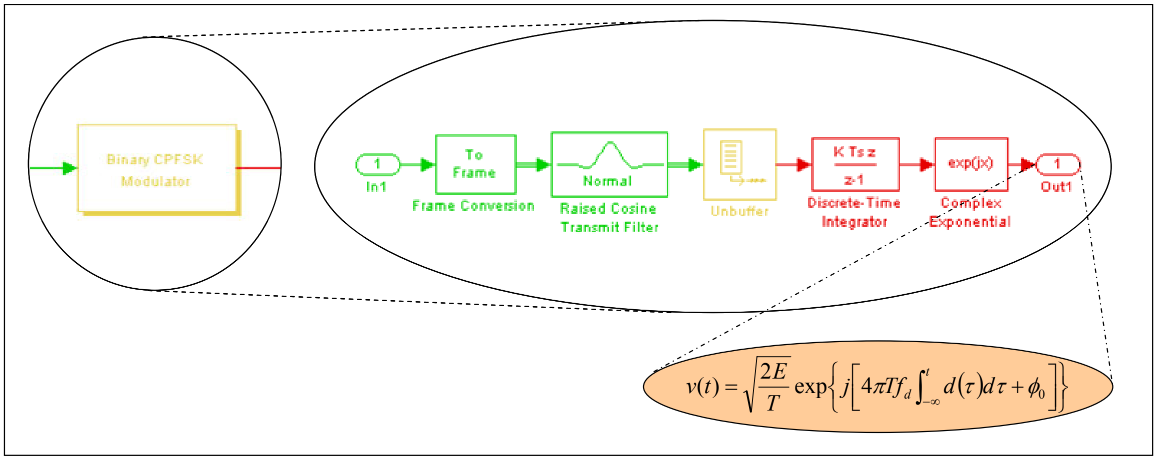


Figure E–35.—LDL Binary CPFSK Modulator Model.

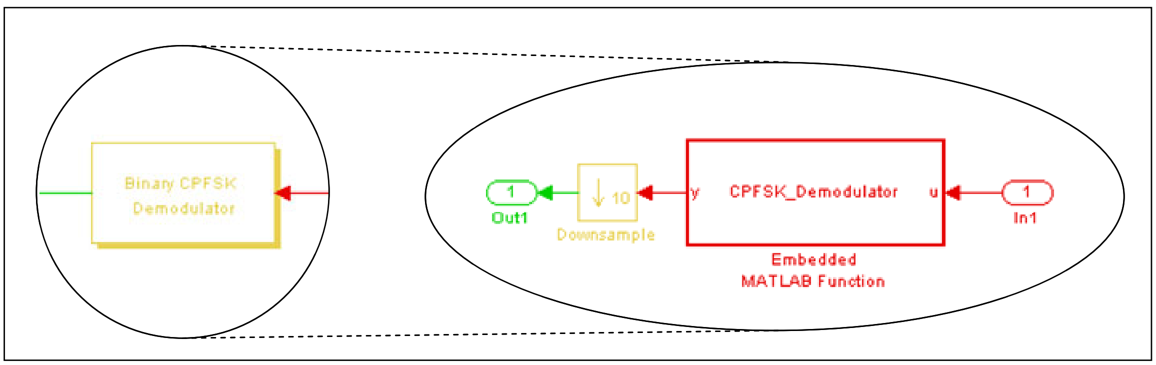


Figure E–36.—LDL Binary CPFSK Demodulator Model.

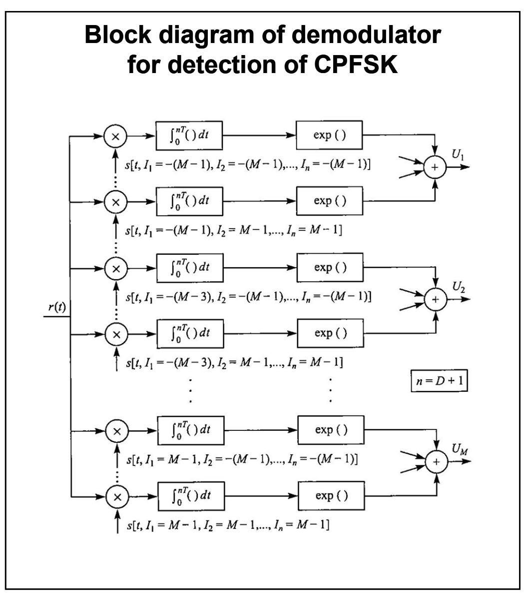


Figure E–37.—CPFSK Demodulator Block Diagram.[137]

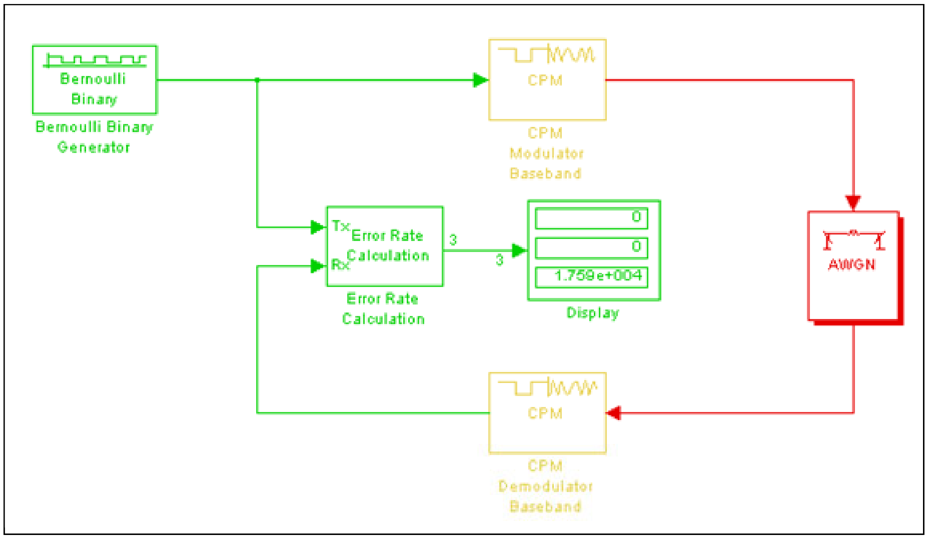


Figure E–38.—LDL End-to-End Simulation (AWGN Channel).

Implementing the simulation models, and during validation simulations, two deficiencies were acknowledged in the custom-coded demodulator. First, the custom demodulator has a 1 to 2 dB implementation loss; second, the custom demodulator runs very slowly. To speed the simulation runtime, the custom implementation was replaced with native Simulink CPM blocks to perform the modulator/demodulator functionality. The end-to-end simulation with an additive white Gaussian noise (AWGN) channel is illustrated in figure E–38.

To validate simulation outputs, theoretical BER curves were compared to simulation results. These curves are shown in figure E–39. Here the theoretical curve is the performance of binary CPFSK with coherent detection using traceback length (n) of 5, and modulation index (h) of 0.715 [Proakis].[138] The simulation model uses the same traceback length (n = 5) and a modulation index (h) of 0.715.

A modulation index of 0.715 was required to validate the model with published results; however, LDL calls for a modulation index of 0.6. Changing the modulation index from 0.715 to 0.6 pushes the BER curve out approximately 1 dB (see figure below). However, the Reed-Solomon (72,62) code defined for LDL provides a coding gain of 3 to 4 dB in the expected region of operation.

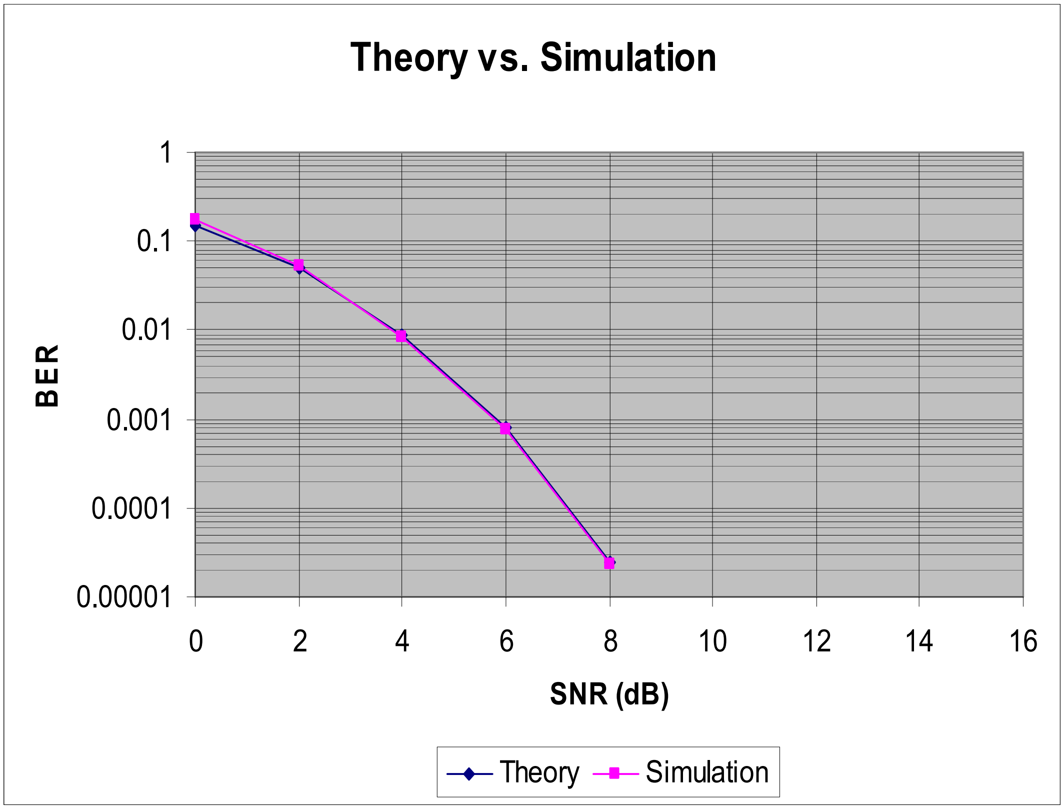


Figure E–39.—Simulated LDL BER Performance Versus Theory.

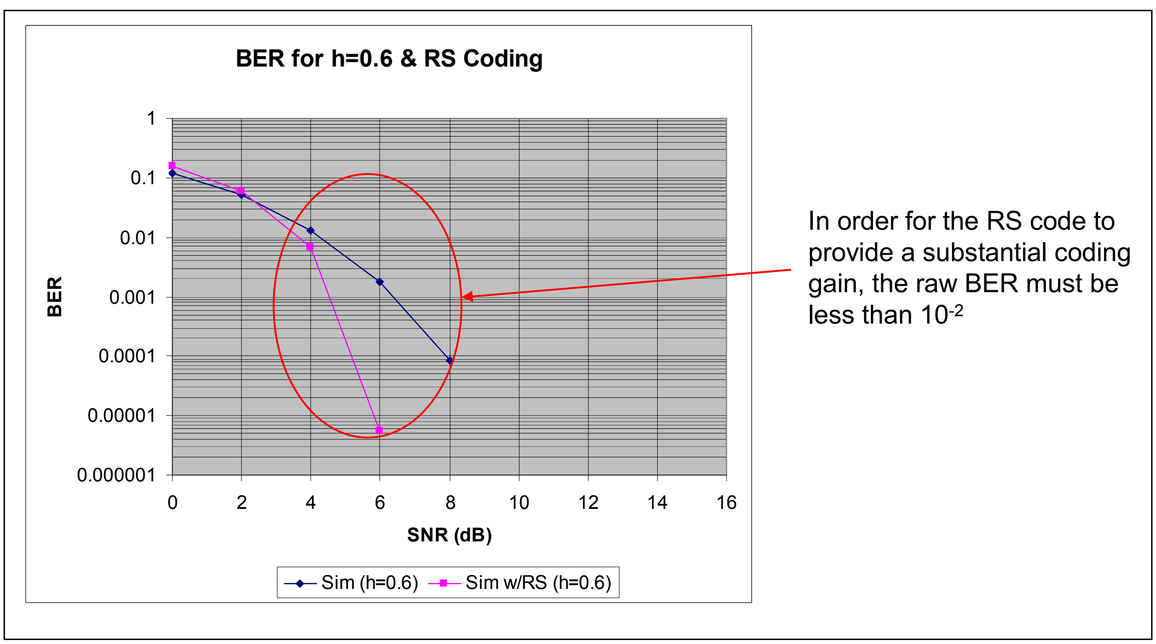


Figure E–40.—Simulated LDL BER With 0.6 Modulation Index.

After validating the end-to-end simulation model, the L-Band aeronautical channel model (described in section E.1.1) was integrated into the simulation. This channel model was implemented as a hierarchical model using native Simulink blocks, as shown in figure E–41.

Using the integrated model, LDL BER performance in both AWGN and the L-Band aeronautical channel model was simulated. These results are shown in figure E–42. In these results, both coherent and noncoherent detection schemes are shown. Here, noncoherent detection has superior performance, but requires equalization.

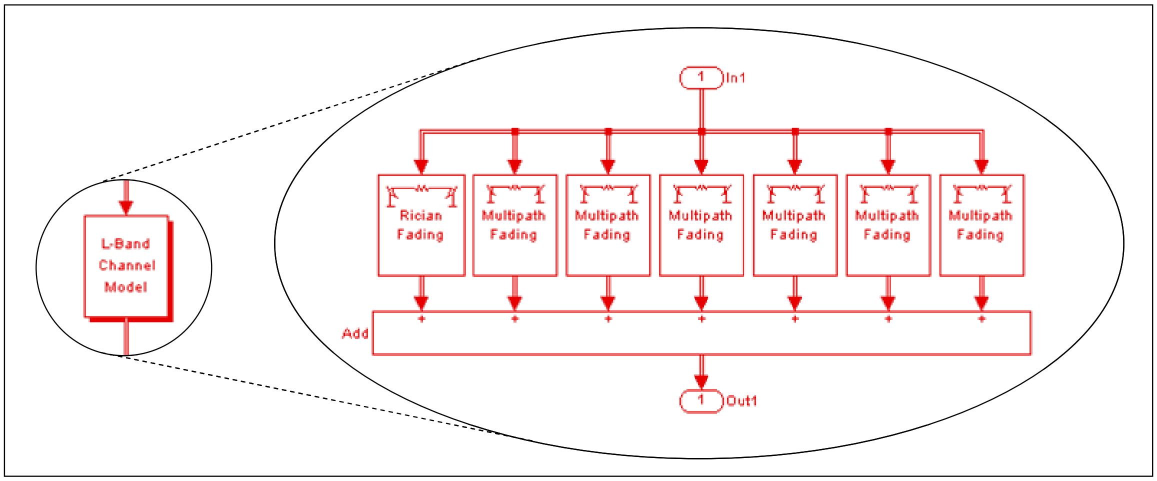


Figure E–41.—L-Band Aeronautical Channel Model (Simulink).

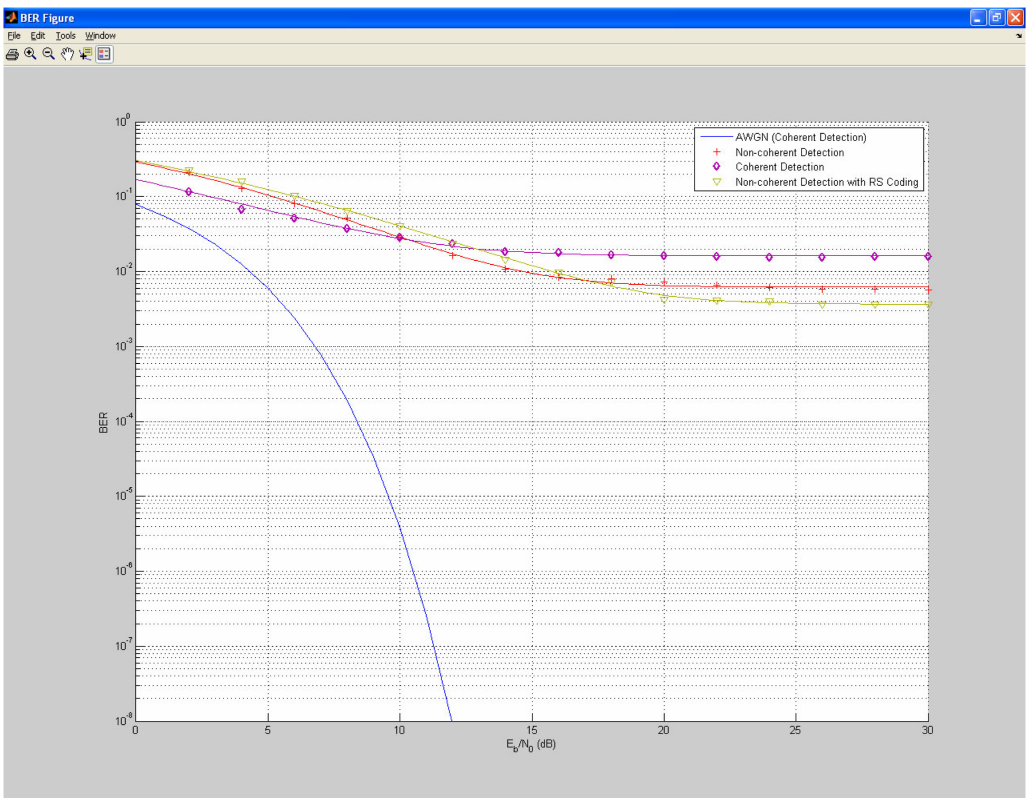


Figure E–42.—LDL BER Performance (AWGN and L-Band Channel).

Considering simulation results, the LDL channel model can be viewed as a conservative model that introduces an irreducible error floor to system performance, which is consistent with a frequency-selective channel theory. Based on the results of this model, LDL will require channel equalization to mitigate the effects of the Air/Ground Aeronautical Channel in L-Band. It should be noted that the LDL simulation was run using a data rate of 62.5 kbps. LDL documentation states that other data rates (i.e., 83.3 kbps, 100 kbps, etc.) are possible, but at these higher data rates, further degradation of system performance is expected. Additionally, note that these are initial results still undergoing validation.

E.1.4 P34/LDL interference analysis

Several candidate technologies for the FRS have been considered in the context of operation in the aeronautical L-Band spectrum. This band, 960 to 1215 MHz, has a primary allocation for Aeronautical Radio Navigation Services (ARNS). There are current several system implementations that occupy the band. ICAO systems that use spectrum in this band include the Universal Access Transceiver (UAT); secondary surveillance radars (including ATCRBS, Modes A and C, and Mode S); and Distance Measuring Equipment (DME). A majority of the spectrum allocations for these systems are standardized by ICAO. There are, however, some exceptions such as DME allocations defined on a national basis between 962 and 977 MHz in the United States.

Additional systems operating in the aeronautical L-Band spectrum include military systems. These include TACAN and JTIDS/MIDS (Link 16). The use of military systems in this band is subject to national coordination between military and civil authorities. Global Navigation Satellite Systems also occupy this band. Specifically, the upper part of the band has been designed for Radio-Navigation Satellite Service (RNSS). A visual depiction of the current and planned L-Band utilization is shown in figure E–43.

As part of the consideration of new future communication system technology implementations in this band, the need to analyze the interference potential of proposed technologies to systems current operating the aeronautical L-Band spectrum has been identified. A generic process for interference analysis would have the following elements:

- Describe the source of interference and the interference mechanism
  - Description is usually in the form of power spectrum and time characteristics (e.g., transmit (Tx) power, transmission bandwidth, and duty cycle)
- Quantify the isolation between transmitter output and receiver input
  - This isolation includes the effects of antenna gains, cabling losses, and propagation
- Determine the ratio of undesired to desired signal power at the input of the receiver decision process (detector)
- Quantify receiver performance as a function of this D/U ratio, and ascribe a required performance and assess compatibility

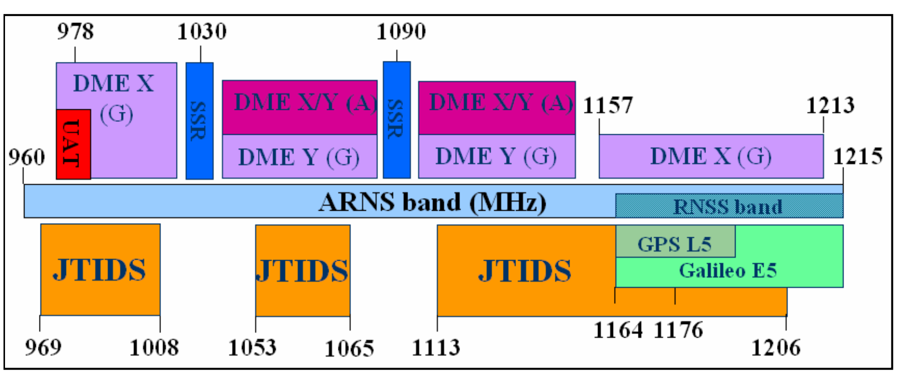


Figure E–43.—Current and Planned L-Band Utilization.[139]

The last item noted above is the most difficult element of the process and was the focus of the interference simulation work defined for this study. Specifically, during consensus FAA, NASA, and ITT deliberations at the beginning of the study, two technologies were selected for detailed analysis, LDL, and P34. At that time, it was determined that the compatibility of those two proposed systems with existing ICAO standardized civil aviation systems would be included in the detailed analysis. Thus, the objective of the interference analysis task was to determine the compatibility of P34 and LDL with standardized civil aviation systems. The approach for the interference analysis included (for each system being analyzed):

- Selection of an appropriate measure of interference degradation
- Collection of information about the system (known susceptibilities, system technical parameters)
- Development of a physical layer system model and validation with known results
- Introduction of the interference source and prediction of victim performance

In an effort to prioritize analysis resources, a list of individual candidate interference analyses was defined. This list is provided in table E–6.

TABLE E–6.—CANDIDATE INTERFERENCE ANALYSES

Interference Source	Victim Receiver	Interference Mechanisms	Source Characterization	Has Vulnerability been characterized?
FRS 960 – 1024 MHz 960 – 977 MHz preferred	GNSS 1176.45 MHz	Broadband Noise Spurious Emissions Desensitization	Noise (WB) NB or CW	Yes Yes
	Mode S 1030 MHz 1090 MHz	Broadband Noise Spurious Emissions Desensitization	Noise (WB) NB or CW	Yes Unknown
	UAT 978 MHz	Adjacent Signal Broadband Noise Spurious Emissions	FRS Dependent Noise (WB) NB or CW	No Yes Yes
	DME 962 – 1019 MHz	Co-channel Adjacent Signal Broadband Noise Spurious Emissions	FRS Dependent FRS Dependent Noise (WB) NB or CW	No No Yes Yes

In table E–6, it can be noted that some of the vulnerabilities have previously been characterized. Therefore, the focus of this study was on the vulnerabilities shaded in red, in other words, those vulnerabilities that have not previously been addressed. The following subsections describe the interference analysis methodologies and results. This information is organized along categories of victim receiver (rather than interference source, i.e., P34 and LDL) as follows:

- DME Interference Modeling—Section E.1.4.1
- UAT Interference Modeling—Section E.1.4.2
- Mode S Interference Modeling—Section E.1.4.3

E.1.4.1 DME interference modeling

The Distance Measuring Equipment (DME) system is an ICAO standardized navigational aid used to determine the aircraft location. It consists of an interrogator located onboard the aircraft and a transponder located at a ground station. At regularly spaced intervals, the interrogator transmits a coded pulse to the transponder. Reception of this pulse triggers a coded reply from the interrogator at a different frequency. The DME system uses the principle of elapses time measurement between these two messages as the basis for determining the distance between the aircraft and the ground station, also called the slant range distance. DME frequencies are spaced in 1 MHz increments throughout the 962 to 1213 MHz band, providing potential for interference to and from FRS in L-Band.

A list of known DME susceptibilities has been captured in table E–7. These include both airborne DME and ground DME susceptibilities.

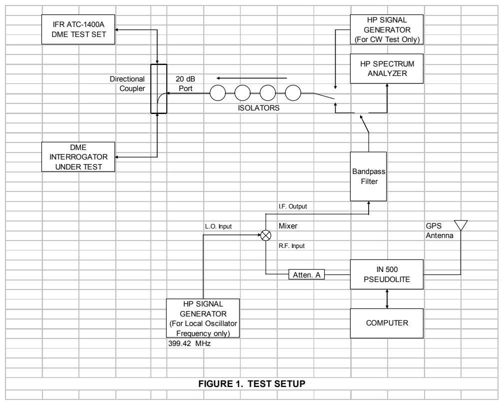
TABLE E–7.—DME KNOWN SUSCEPTIBILITIES

Airborne DME Receiver	On-ground DME Receiver
Co-channel DME signal (1/2) (same frequency and same pulse pair spacing). Accuracy requirements shall be met in presence of 3600 ppps with a minimum C/I = 8 dB (annex 10, Vol. I, section 3.5.5.3.4.1 & EUROCAE ED-54) **Co-channel DME signal (2/2)** (same frequency and different pulse pair spacing). Accuracy requirements shall be met in presence of 3600 ppps with a minimum C/I = -42 dB (EUROCAE ED-54)	**Co-channel DME signal** Not known
Continuous Wave signal (CW) Sensitivity requirement shall be met for: •In-band continuous CW up to -99 dBm •Out-of-band CW up to -40 dBm (EUROCAE ED-54)	**Continuous Wave signal (CW)** Reply efficiency shall remain greater than 70% in presence of in-band continuous CW with a minimum C/I = 10 dB. (EUROCAE ED-57)
JTIDS/MIDS signal Maximum value of -36 dBm at the antenna port based on time-to-acquire requirement. Time slot duty factor (100/50) and minimum vertical separation of 1000 ft. Experimentally verified as part of NATO Common Frequency Clearance Agreement.	**JTIDS/MIDS signal** Tolerated up to -33 dBm at the antenna port based on time-to-acquire requirement. Time slot duty factor (100/50). Experimentally verified as part of NATO Common Frequency Clearance Agreement.
Broadband Interference Maximum value of -99 dBm/MHz within receiver bandwidth based on sensitivity requirement as for the CW case. (Rec. ITU-R M.1639)	**Broadband Interference** Not known

ITU Document 8D/107-E presents the results of measurements that characterize the susceptibility of DME Interrogator-Receiver Avionics to RNSS emissions. Measures are made for a Continuous Wave (CW) signal (as a baseline) as well as for the RNSS C/A and P-codes. Figure E–44 provides the test step associated with these measurements along with actual measurement results.

The results above indicate that despite the huge difference in signal bandwidths (fully 10 dB), the susceptibility of DME to the C/A and P-codes differs by 2 dB. The same effect is seen for Acquire Stable Operating Point (ASOP) and Break Stable Operating Point (BSOP), where ASOP is more sensitive. These results are difficult to conceptualize.

Additional published results were identified from the FAA technical center. Specifically, measurements of UAT interference effects on DME interrogators were reviewed. The test setup and associated measurement results are provided in figure E–45.



Desired DME Signal Level	DME Frequency	Interference level dBm					
		CW		RNSS C/A Code		RNSS P Code	
dBm	MHz	ASOP	BSOP	ASOP	BSOP	ASOP	BSOP
-83	1176	-89	-87	-91	-90	-89	-88

Figure E–44.—DME Susceptibility to RNSS Emissions—Test Setup and Results.

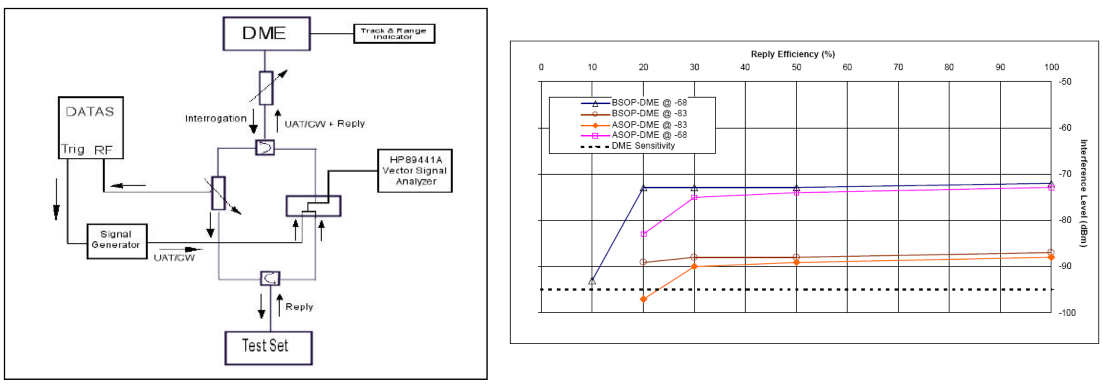


Figure E–45.—DME Susceptibility to UAT—Test Setup and Results.

The UAT/DME testing noted above was performed on three different DME interrogators (Bendix King KD-7000, NARCO DME-890, and Honeywell KDM-706A). The degradation measure selected for this test was ASOP and BSOP.

With the knowledge gained from review of existing DME tests, a first step in the FCS/DME interference analysis was the development of a DME receiver model. To perform this work, published data on DME interference from GPS signals was obtained. The data indicated that interference from P(Y) and from C/A signals does not differ much, even though the P(Y) signal has 10 times larger bandwidth. Thus a hypothesis was developed, which assumes that pulse detection in DME equipment is performed over a short window, on the order of one P(Y) chip length. A receiver window length, which would yielded a match with the published data, was then computed.

In additional to the hypothesis noted above, more general DME architecture operational assumptions were made. These included:

- A unit sends an interrogation pulse pair and then checks for return pulse pairs over multiple short time windows. A pulse pair is detected if the signal level is above some threshold at the expected pulse arrival times, below the threshold between pulses
- If a return pulse pair is detected, N more interrogation pulses are sent. A lock is detected if at least n return pulses are detected
- A lock is lost if the fraction of detected pulses falls below a threshold
- If the return pulse pair was not detected after the first interrogation pulse, the process is repeated up to k times

Based on the hypothesis and assumptions above, a mathematical model, which describes this architecture, was built. The model was run for different values of parameters to determine sets of parameters that matched published results. The implemented model was then tested using a UAT interfering signal to test results. The developed model and associated UAT test results are shown in figure E–46.

For the model, DME pulses were modeled as Gaussian. UAT was modeled as a frequency-shift keying, constant amplitude signal. Here, the DME pulses and interference were superimposed in the time domain. The resulting signal was filtered using a filter with Gaussian response function; the width of the filter response is computed to match a measured decrease of interference effect as a frequency offset of 1 MHz as compared to no offset.

For each filtered pulse, the DME airborne receiver determines the half-amplitude point with respect to the pulse amplitude. The amplitude of a particular pulse may differ from the average amplitude due to interference; however, the half-amplitude point is defined as the timing of the half-amplitude of the average pulse (which is the same as the amplitude of a pulse without interference). For each pulse pair to be received, the half-amplitude timing of two pulses must be separated by the time interval, which is close to 12.5 microseconds. If the measured time separation differs from the nominal value by more than some aperture DT, the pair is tallied as one not received. To acquire lock, there is some minimum percentage of pairs received A_min. To maintain lock, there also is some minimum percentage of pairs received B_min. There is hysteresis in acquisition and maintaining of lock.

A more detailed presentation of simulation results (and simulation parameters) is provided in figure E–47. Here, measured results for Bendix King KD-7000 with simulation results superimposed are shown.

Despite the seemingly good correlation of results of the developed model and measurements, several problems with the developed model were noted during validation testing. Specifically,

- The measured results are extremely flat over the reply efficiency range of the test
  - Indicative of an AGC circuit (perhaps) or some second-order effect that is not immediately obvious
- To create a range of "Acquire Locks" for various reply efficiencies, the interference power for our model had to be varied over a 10 to 12 dB range
  - This was deemed to be sufficiently far from measured results as to be a nonreliable indicator (for use in predicting interference from FRS sources)
- Several requests for information and assistance were made by NASA, but the information that was needed (detailed algorithm descriptions from radio manufacturers) was not made available

As a result of the observations above, a decision was made to not further use the developed model. Rather, measurements are recommended to more substantively characterize the DME to communication waveforms in the final phase of the FCS technology assessment (2006 to 2007).

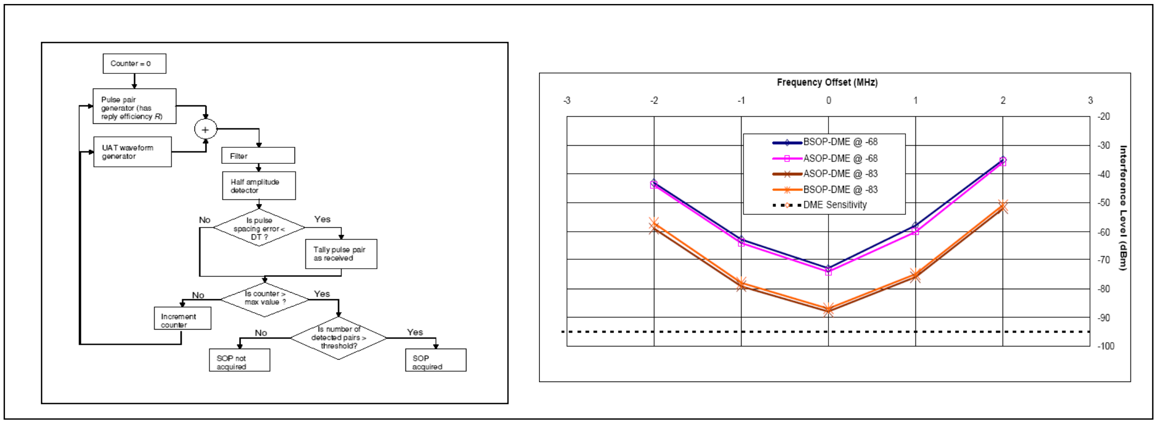
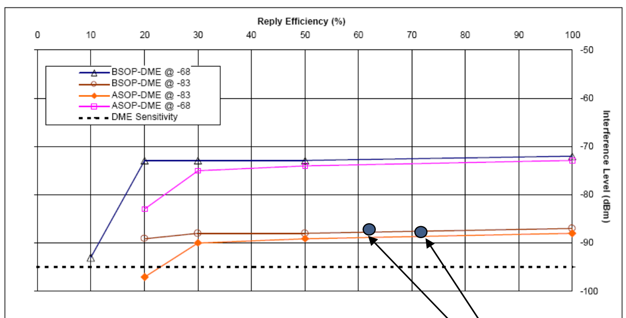


Figure E–46.—Implemented DME Model and UAT Interference Results.



DME power (dBm)	Unit modeled	Interference at 1 MHz offset vs. 0 offset	Aperture DT, micro-seconds	UAT power (dBm)	Percent of pairs received
-83	Bendix King KD-7000	12	3.0	-88.0	61 % BSOP
-83		12		-89.0	73 % ASOP
-83	Honeywell KDM-706A	20	0.7	-95.0	62 % BSOP
-83		20		-96.0	70 % ASOP

Figure E–47.—DME Simulation Result Details.

E.1.4.2 UAT interference modeling

UAT is a wideband data link that enhances pilot situation awareness and increases safety by allowing general aviation pilots to process navigational signals from the Global Positioning System (GPS), receive traffic information, broadcast their position, and perform other functions. It is a technology that is standardized through ICAO for ADS-B, Traffic Information Services—Broadcast (TIS-B), and Flight Information Services—Broadcast (FIS-B). UAT operates at 978 MHz, providing potential for interference to and from a FRS in L-Band.

UAT has several known susceptibilities. These include:

- DME signal interference (basic and high-performance receivers)
  - 99% successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 μs spacing at a level of –30 dBm for any 1 MHz channel frequency between 980 and 1215 MHz (desired signal >= –90 dBm)
- DME signal interference (basic receivers only)
  - 90% successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 μs spacing at a level of –56 dBm for any 1 MHz channel frequency between 979 (desired signal >= –87 dBm)
- DME signal interference (high-performance receivers only)
  - 90% successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 μs spacing at a level of –43 dBm for any 1 MHz channel frequency between 979 MHz (desired signal >= –87 dBm)

For this study, the objective was to characterize the impact of LDL and P34 interference on UAT performance. To perform the analysis, several assumptions were employed. For UAT, the basic ADS-B message code RS(30,18) has been modeled. The analysis did not include long ADS-B message codes RS(48,34) or Ground Uplink Message Codes RS(92,72). For LDL, the transmitter model used a data rate of 62.5 kbps. The analysis did not consider other possible LDL data rates. And finally, for P34, the 50 kHz channelization configuration of P34 was modeled. The analysis did not consider the 100- or 150-kHz configurations. The process for analyzing UAT interference was as follows:

1. Develop UAT end-to-end simulation model using Signal Processing Worksystem (SPW)
2. Validate performance of UAT model against published results for BFSK
3. Integrate Reed-Solomon coding into the end-to-end simulation model
4. Validate performance of UAT model with RS coding against published results for coded BFSK
5. Develop LDL transmitter model and validate PSD
6. Develop P34 transmitter model and validate PSD
7. Integrate LDL and P34 interferer models into UAT end-to-end simulation model
8. Collect and analyze performance data (BER curves) for varying degrees of interference

To perform the steps above, transmitter models were developed for UAT, LDL, and P34. These models supported or addressed steps 1, 5, and 6 above. A block diagram of the UAT transmitter modeled is shown in figure E–48. Figure E–49 identifies the analysis parameters and SPW implementation of the UAT transmitter.

A block diagram of the LDL transmitter modeled is shown in figure E–50. Figure E–51 identifies the analysis parameters and SPW implementation of the LDL transmitter.

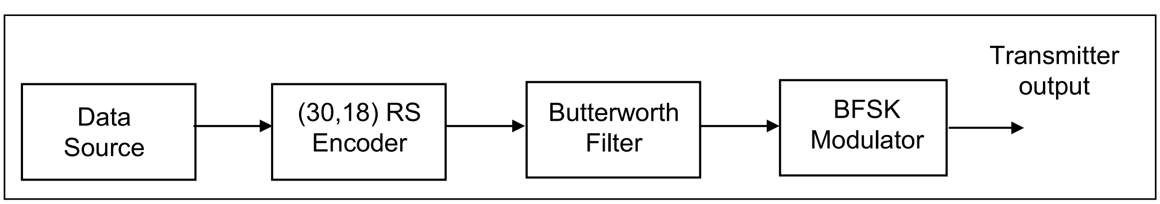
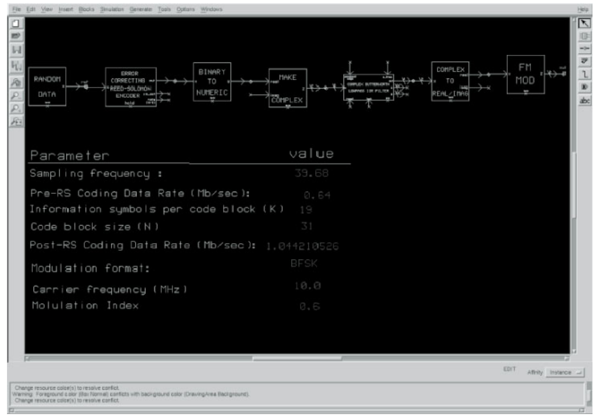


Figure E–48.—UAT Transmitter Block Diagram.

Parameter	Value
Modulation Data Rate	1.05 Mb/sec
Coding	(30,18) Reed-Solomon(1)
Baseband Filter	3rd Order Butterworth
Modulation	BFSK (Modulation index = 0.6)
Notes: 1. Actual simulation model uses a (31,19) RS which should have nearly identical performance as the (30,18), however, without the added simulation complexity of a punctured code	

UAT Parameters Used for Analysis



SPW Implementation of UAT Transmitter

Figure E–49.—UAT Analysis Parameters and SPW Transmitter Implementation.

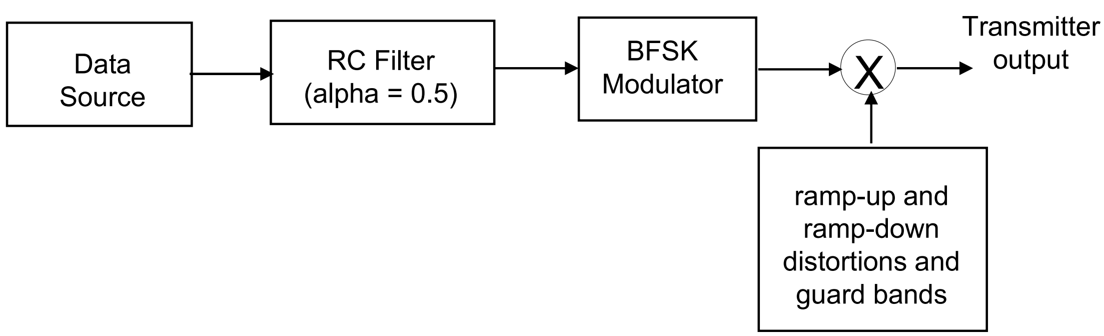
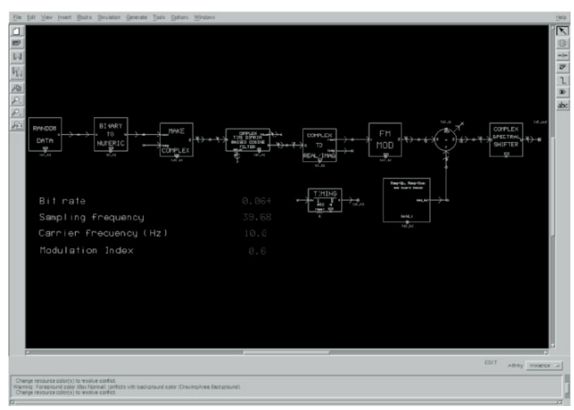


Figure E–50.—LDL Transmitter Block Diagram.

Parameter	Value
Data Rate	62.5 kb/sec
Baseband Filter	RC (alpha = 0.5)
Modulation	BFSK (Modulation index = 0.6)

LDL Parameters Used for Analysis



SPW Implementation of LDL Transmitter

Figure E–51.—LDL Analysis Parameters and SPW Transmitter Implementation.

Finally, a block diagram of the P34 transmitter modeled is shown in figure E–52. Figure E–53 identifies the analysis parameters and SPW implementation of the P34 transmitter.

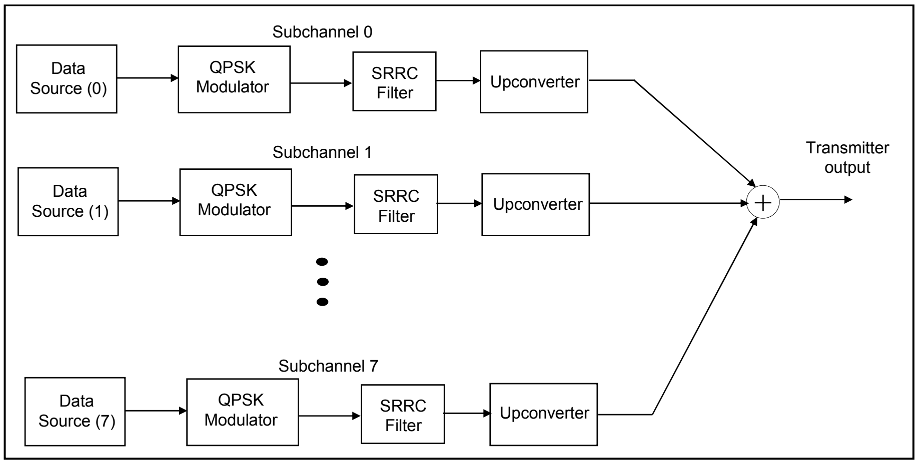
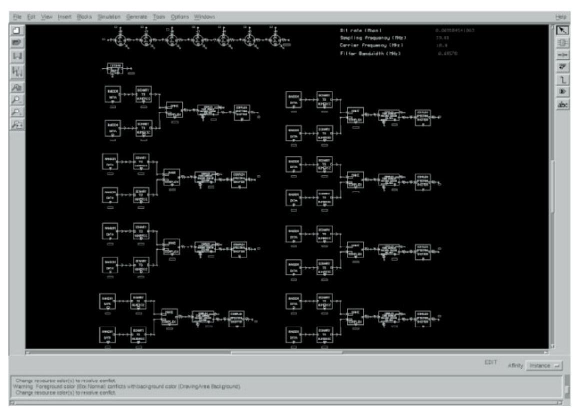


Figure E–52.—P34 Transmitter Block Diagram.

Parameter	Value
RF Subchannels	8$^{(1, 2)}$
Subchannel Spacing	5.4 kHz
Symbol Rate	4.8 kb/sec
Baseband Filter	SRRC (alpha = 0.2)
Modulation	QPSK

Notes:
1. 50 kHz channel configuration
2. Subchannel center offset frequencies are -18.9 kHz, -13.5 kHz, -8.1 kHz, -2.7 kHz, +2.7 kHz +8.1 kHz, +13.5 kHz, +18.9 kHz

P34 Parameters Used for Analysis



SPW Implementation of P34 Transmitter

Figure E–53.—P34 Analysis Parameters and SPW Transmitter Implementation.

Along with development of all individual transmitter models, a complete end-to-end simulation model was created for UAT. A snapshot of this simulation model is shown in figure E–54.

To assess the validity of the developed model (step 2 of the identified analysis methodology), simulations were run end-to-end with only AWGN degradation. Results compared favorable to theory as shown in figure E–55.

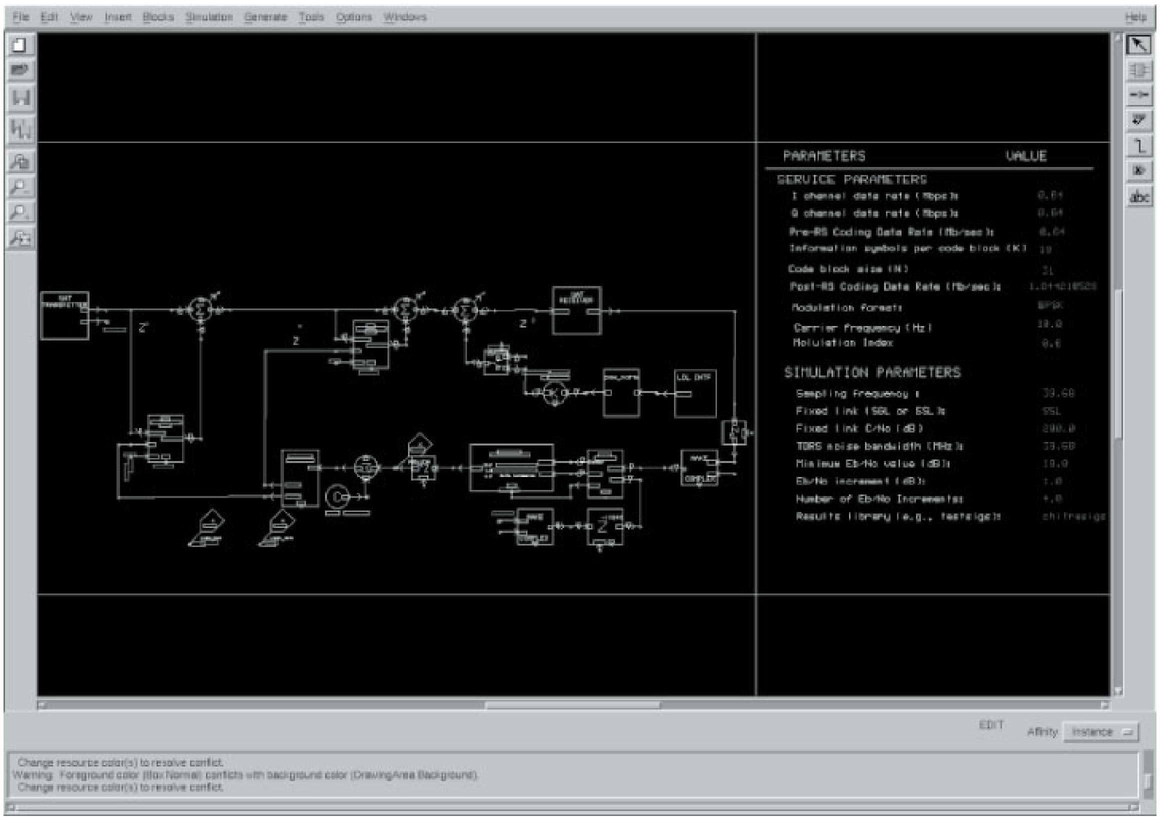


Figure E–54.—UAT End-to-End Simulation Model.

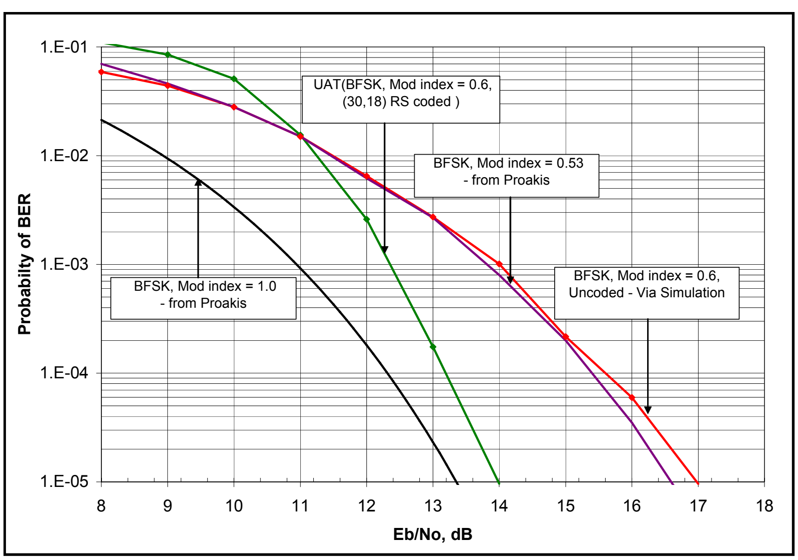


Figure E–55.—UAT Performance in AGWN—Theory and Simulated.

After validation of initial results in AGWN, Reed-Solomon coding was added to the end-to-end simulation. For this analysis, the actual punctured 8-bit code that is defined for UAT was estimated using a native 5-bit Reed-Solomon code. This native code was modeled as it is very difficult to model puncture code in SPW. To validate the assumption of a 5-bit Reed-Solomon code, a simulation was developed in MATLAB Simulink to model the performance of both codes (note that the punctured code is trivial to model in Simulink). Figure E–56 shows good agreement between the two codes (simulated and actual). It is understood that the integrity of the codes differ, but that information was not leveraged in this analysis.

Using the end-to-end model with coding, SPW end-to-end simulation results were generated to identify a collection of BER curves for varying degrees of LDL interference into the UAT signal. These results are shown in figure E–57.

Simulation results were also generated for P34. Again, a collection of BER curves for varying degrees of P34 interference into the UAT signal were generated, as shown in figure E–58.

From the curves above, it would appear that a carrier to interference (C/I) ratio between 12 and 15 dB is required for minimum degradation to the UAT receiver. LDL has slightly better performance than P34 in terms of not interfering with UAT receivers.

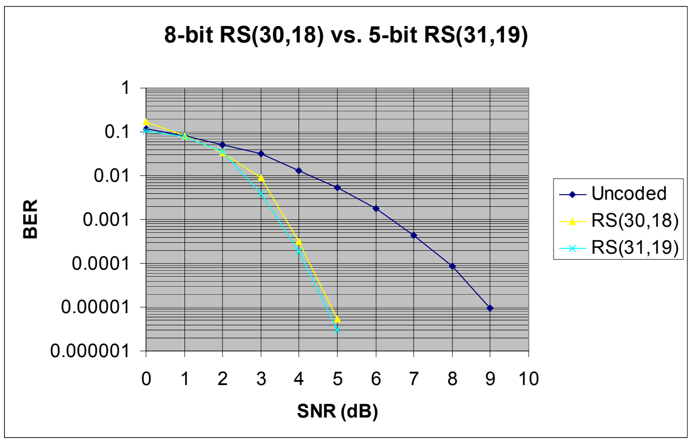


Figure E–56.—UAT Simulated Code Performance.

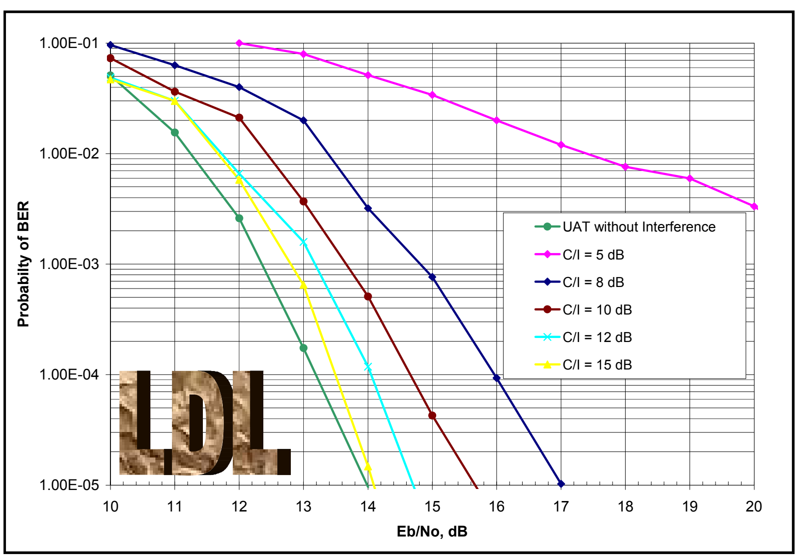


Figure E–57.—UAT Performance in the Presence of LDL.

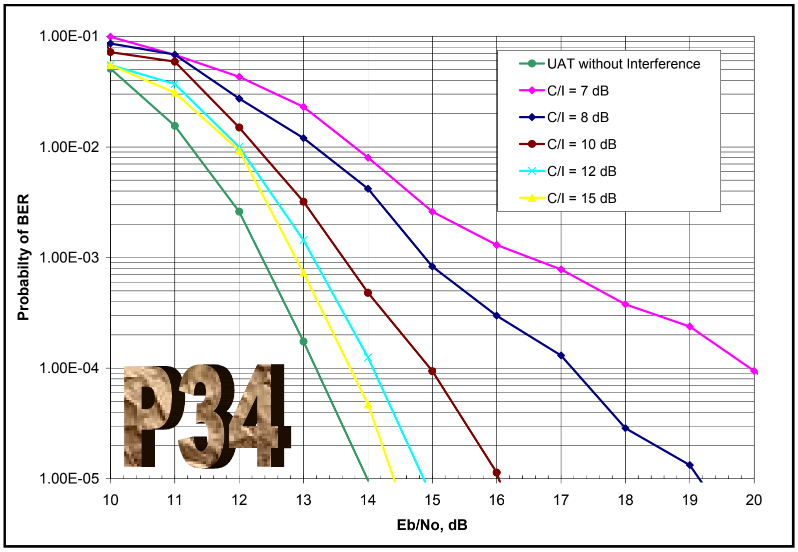


Figure E–58.—UAT Performance in the Presence of P34.

E.1.4.3 Mode S interference modeling

Mode Select (Mode S) is a system developed to phase out the Air Traffic Control Radar Beacon System (ATCRBS) by providing enhanced surveillance information for use by Air Traffic Control automation Mode S provides more accurate position information and minimizes interference by discreet interrogation of each aircraft. Each aircraft has its own unique Mode S address, providing a mechanism by which an aircraft can be selected/interrogated such that no other aircraft reply. Mode S also provides a digital data link to exchange information between aircraft and various ATC functions and weather databases. The system operates at 1030 and 1090 MHz providing a potential for interference to and from a FRS in L-Band.

The developed Mode S transmitter simulation model exactly met the rise-time, decay-time and PSD mask requirements given in the Mode S MOPS. The developed simulation modeled the Mode S preamble detection circuit, making a hard decision on every 0.5 microsecond symbol. Selectable sensitivity is also included in model. Using the developed Mode S transmitter and preamble detection models, an end-to-end simulation was created. This end-to-end model included integrated LDL and P34 interferer models.

Mode S signal characteristics used in the simulation model are shown in table E–8.

TABLE E–8.—MODELED MODE S SIGNAL CHARACTERISTICS[140]

Parameter	Value
Preamble Length	8.0 Microsec
Data Block Length	112.0 Microsec
Parity Check Bits	On AP field (24 bits)
Data Rate	1 Mb/sec
Modulation	Pulse - Position Modulation
Filter	Gaussian (1)
Notes: 1. Bandwidth assumed to meet the rise-time decay-time and PSD mask requirements given in Reference [1]	

An overview of the Mode S transmitter simulation model block diagram is provided in figure E–59.

To validate the Model S transmitter model, a comparison was made between the modeled transmitter's predicted emissions and the specified Mode S mask. This is shown in figure E–60.

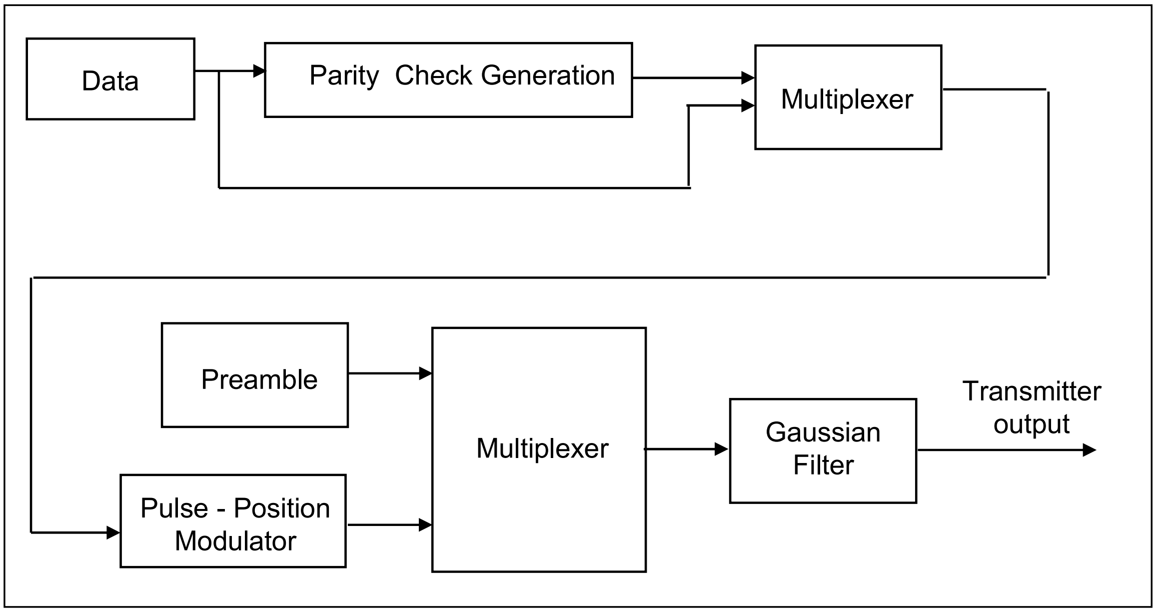


Figure E–59.—Overview of Mode S Transmitter Simulation Block Diagram.

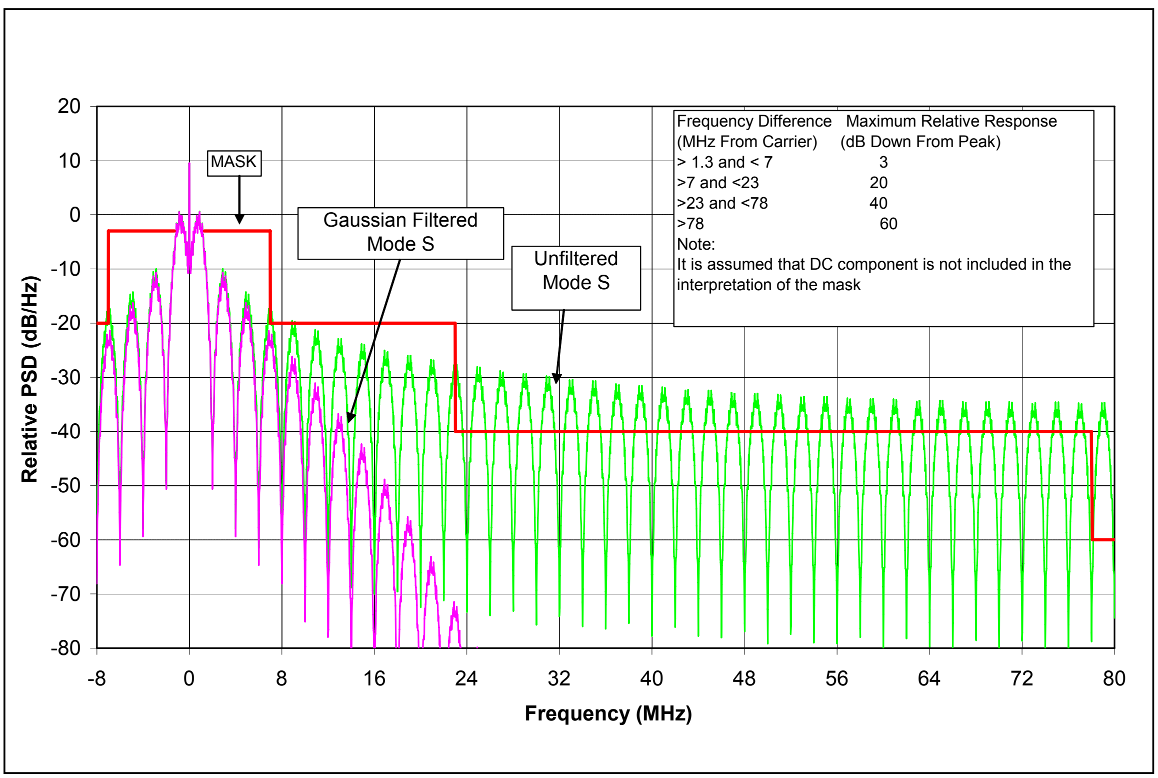


Figure E–60.—Comparison of Mode S Predicted Emissions to Specified Mask.

Figures E–59 and E–60 show the filtered performance of the transmitter model falling within the specified mask. The transmitter model was then incorporated into a Mode S end-to-end model, including interferer sources. The block diagram of end-to-end model is shown in figure E–61.

The simulation described was run to evaluate Mode S performance with LDL interference at the Mode S center frequency. The probability of correct preamble detection curves are shown in figure E–62. The resulting curves on the left are based on an algorithm assumption to declare preamble detection based on 94% correlation; the curves on the right are for declaration of preamble detection with 100% correlation.

Resulting probability of false preamble detection curves are shown in figure E–63.

The simulation described above was also run to evaluate Mode S performance with P34 interference at the Mode S center frequency. The probability of correct preamble detection curves are shown in figure E–64. As before, the resulting curves on the left are based on an algorithm assumption to declare preamble detection based on 94% correlation; the curves on the right are for declaration of preamble detection with 100% correlation.

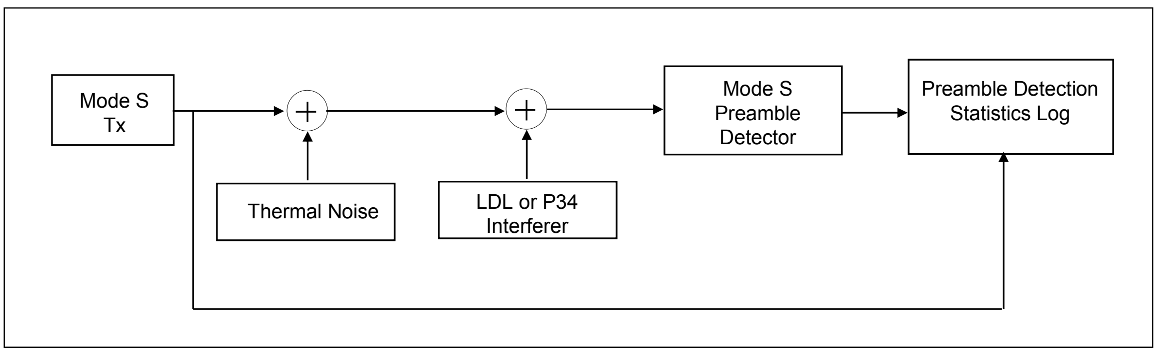


Figure E–61.—Mode S End-to-End Simulation Model Block Diagram.

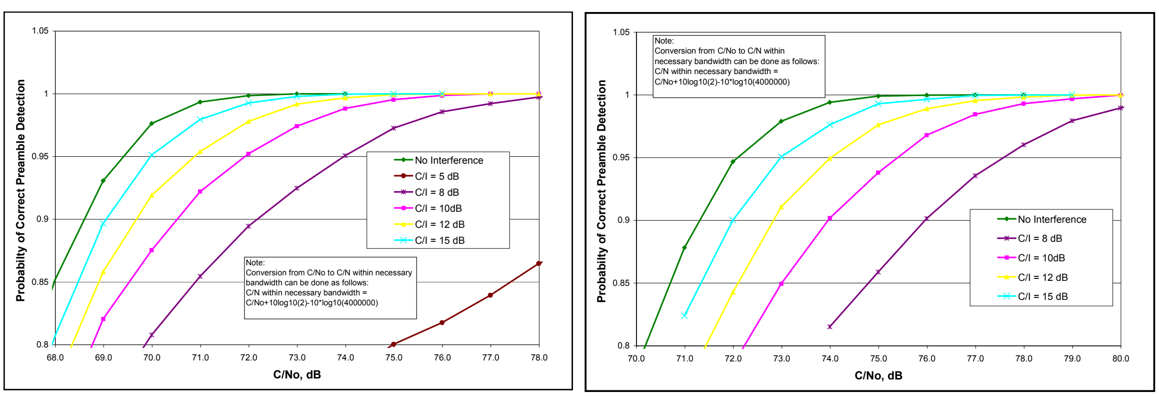


Figure E–62.—Mode S Probability of Correct Preamble Detection—LDL Interferer.

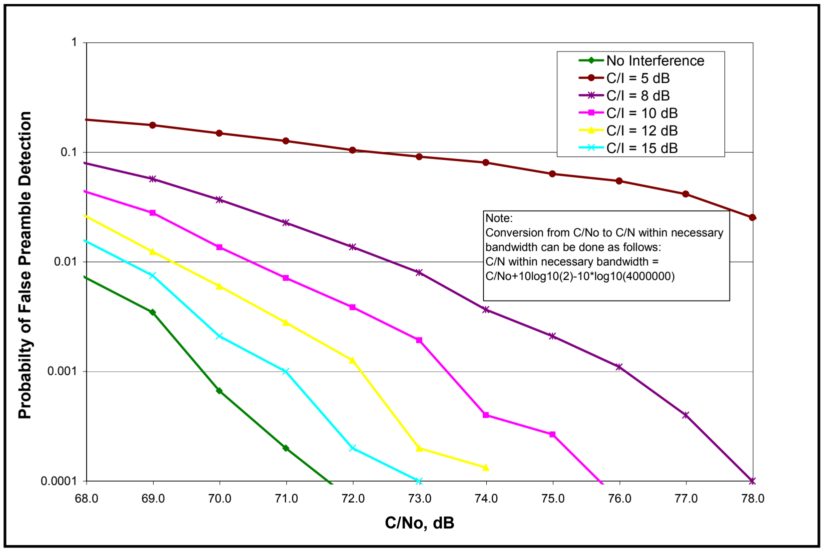


Figure E–63.—Probability of False Preamble Detection—LDL Interference.

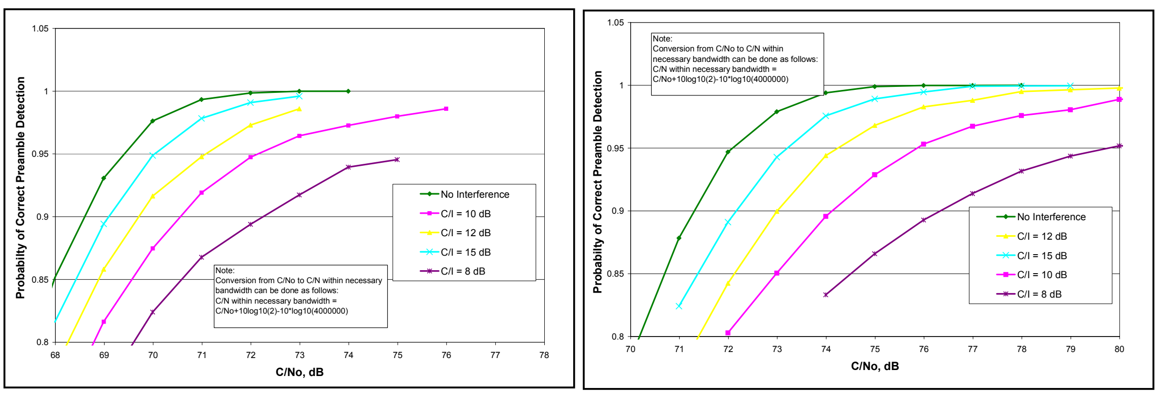


Figure E–64.—Mode S Probability of Correct Preamble Detection—P34 Interferer.

Resulting probability of false preamble detection curves are shown in figure E–65.

To compare the interfering effects of P34 and LDL, a probability of correct preamble detection based on varying C/I values (again for 94% correlation and 100% correlation for declaring detection) for both P34 and LDL interferers are shown in figure E–66.

A similar comparison of interfering effects for Mode S probability of false preamble detection is shown in figure E-67.

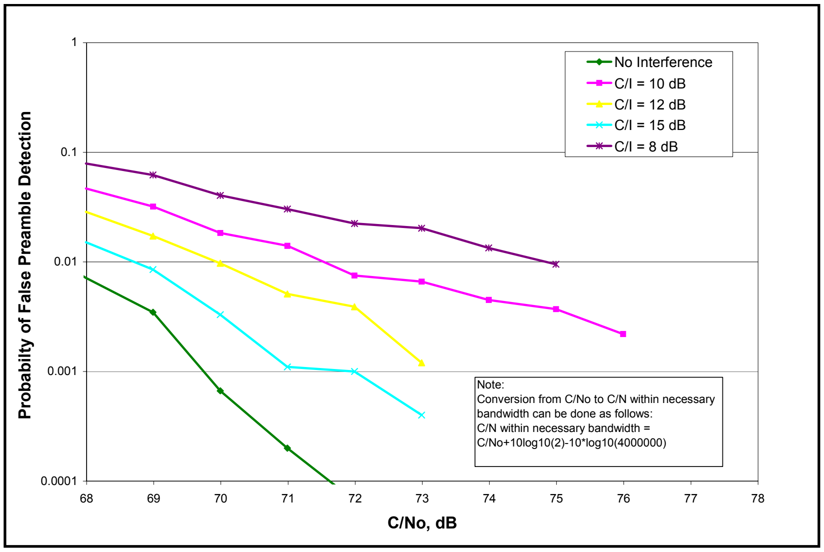


Figure E–65.—Probability of False Preamble Detection—P34 Interference.

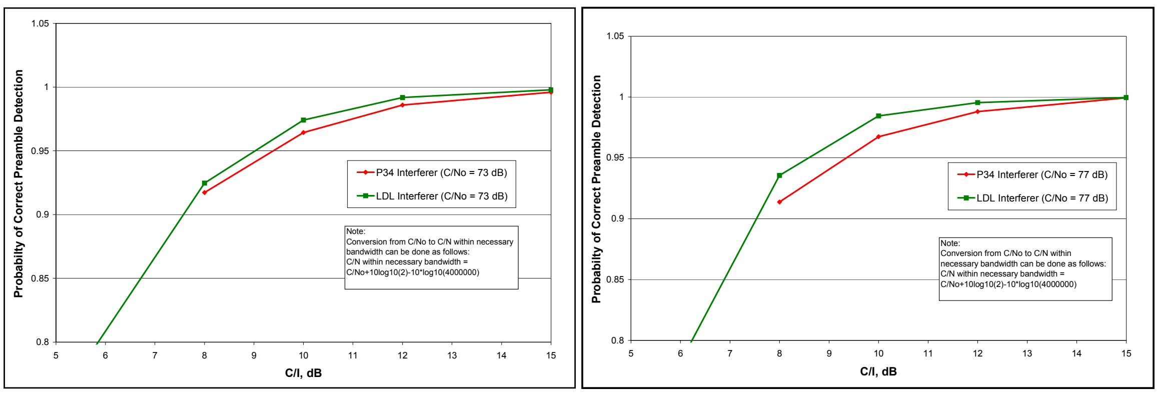


Figure E–66.—Comparing Effects of P34 and LDL Interference on Mode S—Preamble Detection.

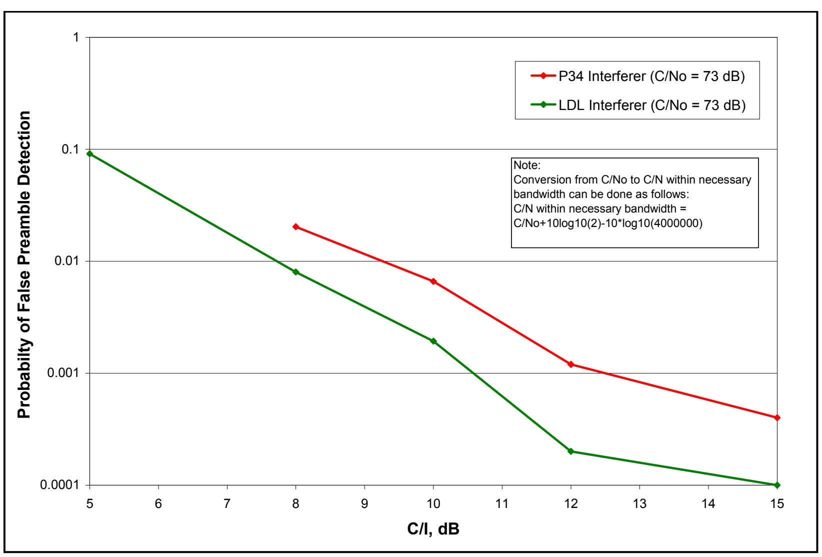


Figure E–67.—Comparing Effects of P34 and LDL Interference on Mode S—False Preamble Detection.

The modeling results would seem to indicate that a C/I ratio of 15 dB or better is required to not substantially degrade the Mode S preamble detection performance. The behavior of "false preamble detection" would appear to be somewhat worse than the behavior of "missed preamble detection." As in the UAT case, the performance of LDL is better than that of P34, that is, P34 acts as more of an interference source than LDL to both Mode S and UAT receivers. It should be noted that all simulations were made "on-tune;" actual deployment scenarios should be far off-tune, especially for the Mode S case (proposed band for the FRS is 960 to 1024 MHz, and the Mode S Extended Squitter equipment is at 1090 MHz). Additionally, measurements should be made that further characterize Mode S behavior as there are other metrics to investigate besides preamble detection. Finally, the preamble detection modeled here is hardly sophisticated, and better performance from actual equipment is predicted.

E.1.5 W-CDMA Assessment

To be performed (2006 to 2007)

E.1.6 B-VHF (At L-Band) Assessment

To be performed (2006 to 2007)

E.1.7 L-Band E-TDMA Assessment

To be performed (2006 to 2007)

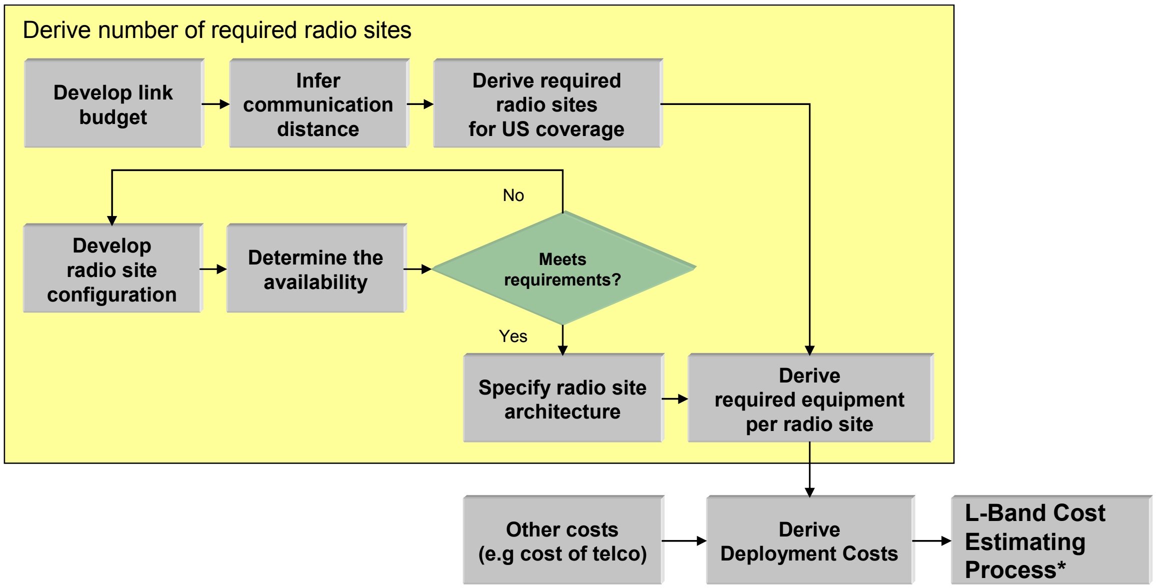
E.1.8 L-Band Business Case Analysis

Future FAA policy might be shifting towards leasing of infrastructure as opposed to ownership of assets. As currently developed, the NAS is a massive infrastructure with correspondingly massive Operations and Maintenance (O&M) costs. Additional ground infrastructure; however, functional or necessary, may simply not be affordable. Therefore, development of an air-ground data communications network at L-Band might never be accomplished by the FAA due to financial constraints.

On the other hand, the commercial deployment of such infrastructure, if encouraged and subsidized by the FAA, will require a business case showing expedient returns on initial investments and associated O&M costs. The objective of the Business Case Development task is to determine if the business case can close. The technical approach for accomplishing this objective is:

- Through detailed analysis, develop a notional ground L-Band architecture that can meet Future Communication Infrastructure (FCI) requirements as defined in the Communications Operating Concept and Requirements (COCR) for the FRS document for ATC communications
  - Derive number of radio sites required for total U.S. coverage
    - Perform L-Band link budget analysis
      - Develop L-Band link budget spreadsheet and derive the parameters to close the link
      - Excess path loss derivation
    - Perform L-Band coverage analysis
    - Derive radio site redundancy to meet system availability requirements
    - Develop an architecture to meet availability required
- Determine if the business case can close
  - Develop cost elements and estimates for initial development and O&M
  - Determine required revenue flow to close business case

The technical approach work flow is shown on figure E–68.



*The L-Band cost estimating process is described in detail later in the report

Figure E–68.—Technical Approach Work Flow.

E.1.8.1 Develop link budget

Link budget is the calculation required to assess the actual system performance in a particular application (in our case, L-Band.) System technical parameters dictate the coverage area that a radio site can provide at any given time. Three major components of system technical parameters and several subcomponents are:

- Link Powers
- Transmit Power
- Noise Power
- Link Gains
- Antenna gains
- Additional gains (e.g., diversity reception, special coding, or array processing)
- Link Losses
- Transmission-line losses
- Propagation loss
- Shadowing/fade margin (excess path loss)
- Implementation losses (both in the transmitter and the receiver)

Many of the link budget technical parameters are technology dependent: data rate and modulation type, which drives required Eb/No, are examples of this. To leverage prior studies, the underlying technology for this analysis is the "LDL." Several resources exist that describe this technology and suggest values to be used in link budget calculations. Most relevant sources are listed below:

- Dr. Wilson, W., June 2005, "An L-Band Digital Communications Link Concept for Air Traffic Control" The MITRE Corporation, McLean Virginia (MP05B0000018)
- RTCA, Inc. DO-224B, August 3 2005, "Signal In Space Minimum Aviation System Performance Standards (MASPS) For Advanced VHF Digital Data Communications Including Compatibility With Digital Voice Techniques" (appendix L Preparation of Link Budgets for VHF Data Link)
- RTCA, Inc. DO-282A, July 29 2004, "Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance—Broadcast (ADS-B)"

These references were used to develop the L-Band Link Budget spreadsheet, which can be used to derive communications coverage. The link budget as shown on table E–9 closes at 160 nmi.

TABLE E–9.—L-BAND LINK BUDGET

v05	***L-Band link budget***	*L-Band link budget Gr = 6.0dBi*
1	Slant Range (nmi)	160.0
2	Ground Antenna Height (ft)	50.0
3	Frequency (MHz)	1024.0
4	Transmitter Power (watts)	25.0
5	Transmitter Power (dBm)	*44.0*
6	Transmit Antenna Gain (dBi)	-4.0
7	Transmit Line Losses (dB)	3.0
8	Transmit EIRP (dBm)	*37.0*
9	Free Space Loss (dB)	*142.1*
10	Excess Path Loss (dB)	4.0
11	Receive Antenna Gain (dBi)	6.0
12	Receiver Line Loss (dB)	2.0
13	Receiver Signal Level (dBm)	*-105.1*
14	Receiver Noise Figure (dB)	5.3
15	Receiver Noise Power Density (dBm/Hz)	*-168.7*
16	Total System Noise Power in specified Data Rate (dBm)	*-118.7*
17	Data Rate (kHz)	100.0
18	Theory Es/No for a BER of 0.001	9.0
19	Raised Cosine Filter Loss (dB)	1.8
20	Transmitter Implementation Loss (dB)	1.0
21	Receiver Implementation Loss (dB)	1.2
22	Required Es/No (dB)	*13.0*
23	Required Receiver Sensitivity (dBm)	*-105.7*
24	Es/No Availabale (dB)	*13.6*
25	Residual System Margin (dB)	*0.6*

From the list of parameters used for link budget calculations, two parameters required detailed analysis. Excess Path Loss (item 10) was calculated from statistics derived from multiple iterations of the IF-77 Electromagnetic Wave Propagation Model (Gierhart-Johnson) model for slightly rolling plains terrain. Data rate (item 17) was selected at 100 kHz based on analysis of capacity requirements in United States in the 2020 to 2025 timeframe.

Having established the maximum range, in this case slant range, of 160 nmi, the required radio sites for U.S. coverage can be derived. A “laydown” for radio coverage in a region of interest was developed. A notional radio placement to provide complete coverage above FL180 in CONUS is shown in figure E–69.

In addition, a notional radio placement was developed to provide complete Alaska and Hawaii coverage as shown on figure E–70.

The total number of radio sites required for coverage above FL180 in CONUS, Alaska, and Hawaii was 66.

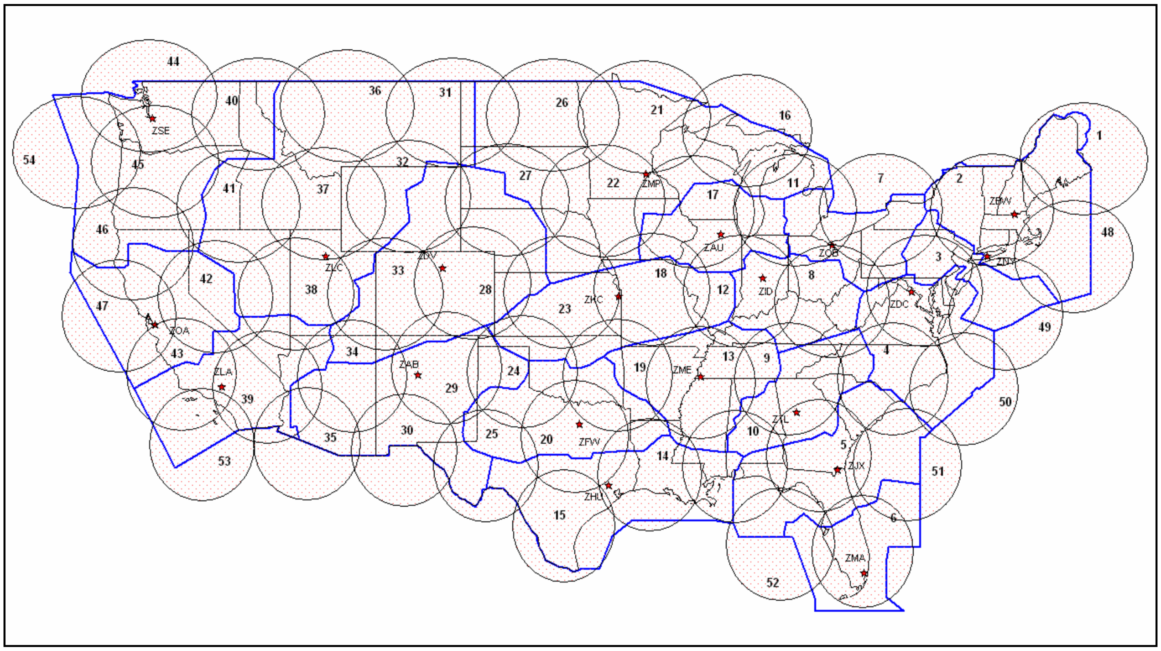


Figure E–69.—Radio Coverage Above FL180 CONUS.

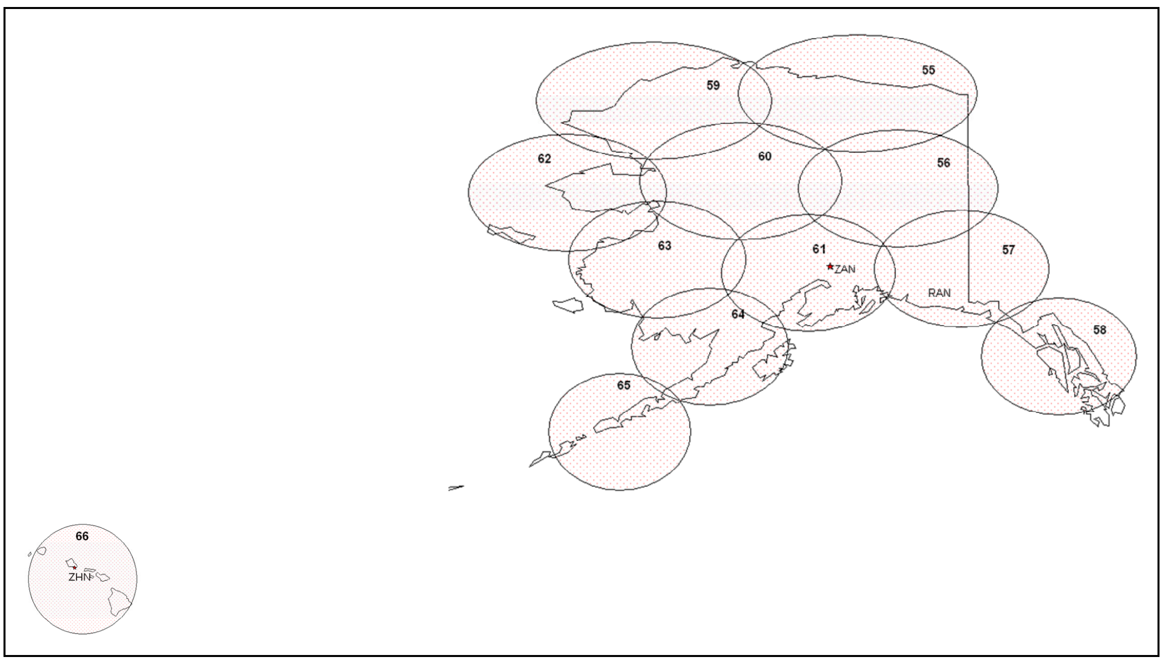


Figure E–70.—Radio Coverage Above FL180 Alaska and Hawaii.

E.1.8.2 Derive radio site redundancy

The workflow shown in figure E–71 describes the necessary steps needed to derive the radio site redundancy and architecture that would meet system availability requirements.

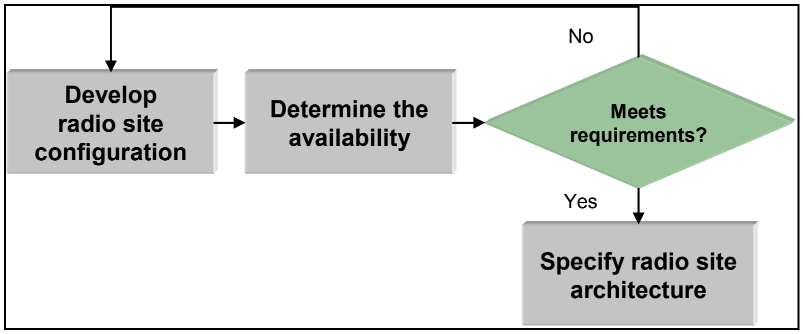


Figure E–71.—Radio Site Redundancy and Architecture Derivation Workflow.

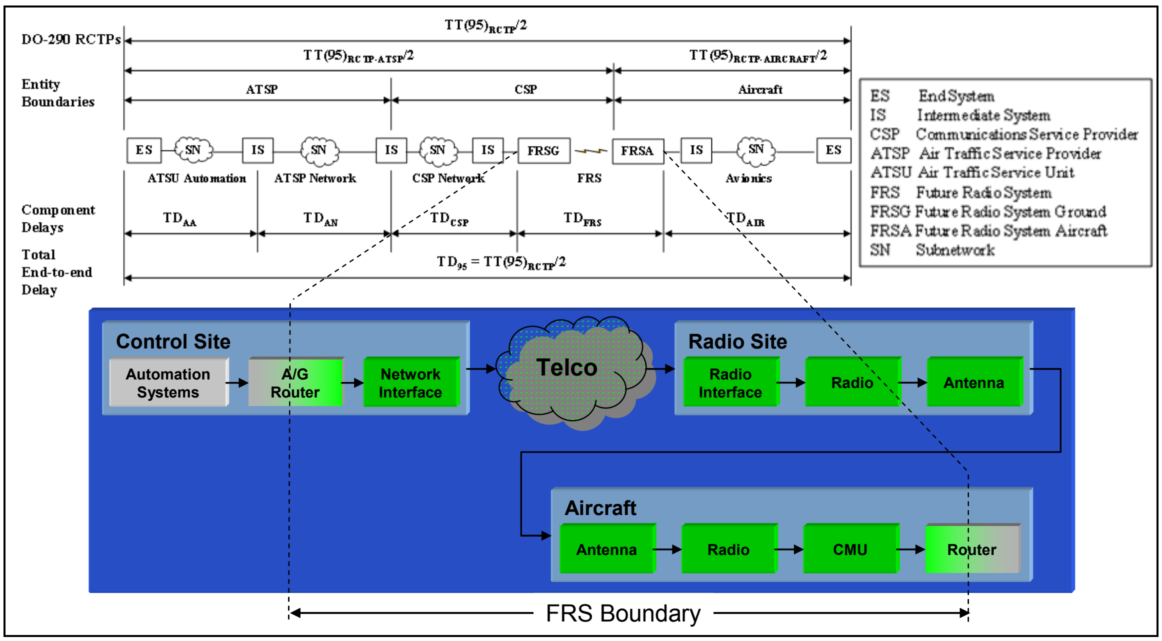


Figure E–72.—FRS Boundary Hardware Equipment.

The COCR specifies the FRS availability requirements in two ways, “availability of use” and “availability of provision” (definitions, adapted from DO-264, are provided below):

- Availability of Use: Availability of use is the probability that the communication system between the two parties is in service when it is needed.
- Availability of Provision: Availability of provision is the probability associate with loss of service to all aircraft in the area.

In addition, COCR availability requirements apply to certain boundary points and are defined by Operational Services, mapped into Classes of Service, and assigned by FRS phase (corresponding to COCR Phases 1 or 2) and by flight domain. COCR Phase 1 en route requirements are 0.9995. COCR Phase 2 en route requirements are 0.99999995. Several architectures were assessed to arrive at a candidate architecture that comes close to the COCR Phase 2 required availability of provision. (Availability of provision requirements are most stringent.)

The boundary of the FRS is defined as the interface to a Subnet Dependant Conversion Facility (SNDCF), a logical rather than physical boundary point. Figure E–72 shows the architecture physical elements corresponding to FRS boundary points. Not all elements are necessary components of “availability of provision” model.

The next step was to allocate the requirements. From the definitions, the two availability requirements are against different sets of hardware equipment. Since it is inconceivable that all of the aircraft systems could simultaneously fail, from an availability of provision standpoint, the availability of the aircraft systems is one. Figure E–73 shows the availability extent for the two availability definitions.

The FRS boundary for the availability of provision includes the following hardware:

- A/G Router
- Network Interface
- Telco
- Radio Interface
- Radio
- Antenna

The method of progressive expansion was used to calculate the availability of radio site configuration that includes the hardware equipment described above. Several radio configurations were examined in order to closely meet availability requirements with the main goal of maintaining architecture cost at reasonable level. "NEXCOM Reliability, Maintainability, and Availability (RMA)" and "Next Generation Air/Ground Communications" documents were the main sources for the approach used to calculate the radio site availability and the configuration parameters values. Figure E–74 shows the configuration of the main radio that was used in the radio site.

Excel was used to calculate the availability of the main radio configuration. Figure E–75 shows the calculation values for the availability numbers.

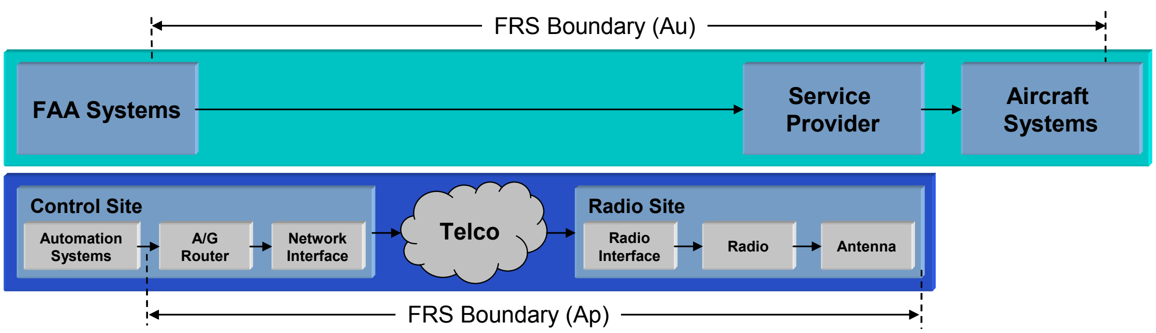


Figure E–73.—FRS Boundaries for Availability of Use and Availability of Provision.

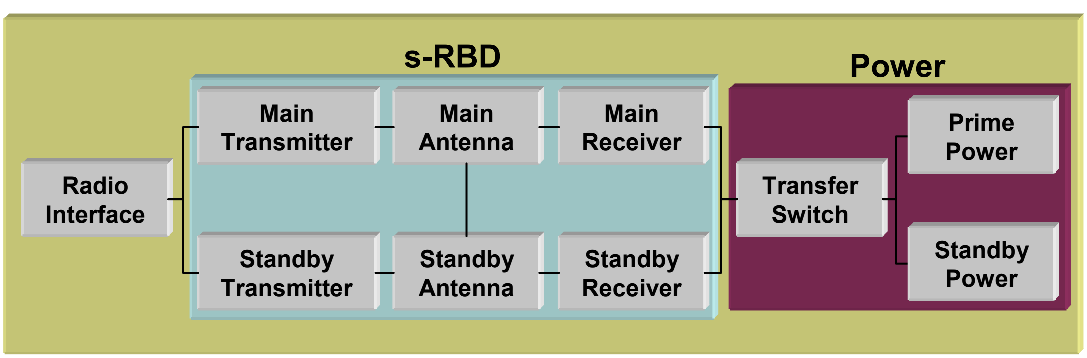


Figure E–74.—Main Radio Configuration.

RMA Analysis	MTBF (hrs)	MTTR (hrs)	Availability
Radio Interface	40000	0.5	0.999987500
s-RBD			0.999999999
Power			0.999996925
Main Radio Configuration			**0.999984425**
Main Tx	52560	0.5	0.99999049
Main Ant.	52560	0.5	0.99999049
Main Rx	52560	0.5	0.99999049
Standby Tx	52560	0.5	0.99999049
Standby Ant.	52560	0.5	0.99999049
Standby Rx	52560	0.5	0.99999049
s-RBD			**0.999999999**
Prime Power	5662	0.5	0.9999117
Standby Power	52560	0.5	0.999990487
Transfer Switch	162666	0.5	0.999996926
Power			**0.999996925**

Figure E–75.—RMA Analysis for the Main Radio Configuration.

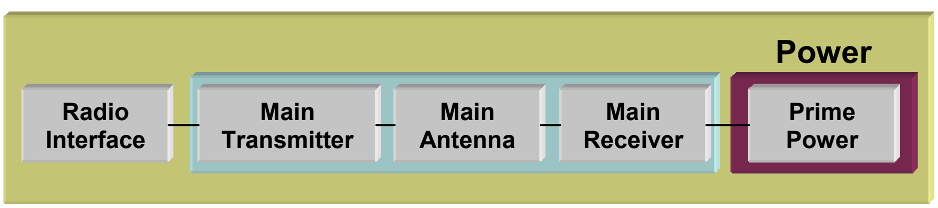


Figure E–76.—Backup Radio Configuration.

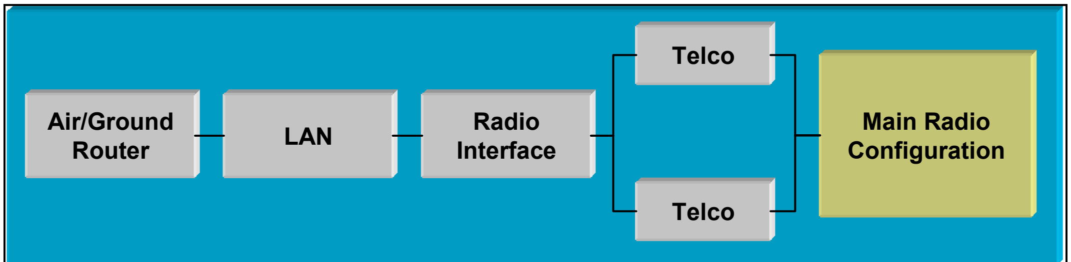
RMA Analysis	MTBF (hrs)	MTTR (hrs)	Availability
Radio Interface	40000	0.5	0.999987500
Main Tx	52560	0.5	0.99999049
Main Ant.	52560	0.5	0.99999049
Main Rx	52560	0.5	0.99999049
Prime Power	5662	0.5	0.9999117
Backup Radio Configuration			**0.999870666**

Figure E–77.—RMA Analysis for the Backup Radio Configuration.

During the process of constructing a radio architecture that would achieve the availability requirements, a need for a backup radio was identified. The backup radio consists of one single string of components. From the availability configuration point of view, the backup radio will be used to increase the availability of the overall radio architecture design. Figure E–76 shows the configuration of the backup radio and figure E–77 shows the calculation values for the availability numbers.

The radio is one element of the overall radio site configuration. At this point other elements of the radio site can be considered and availability calculated. Several potential architectures were examined in order to achieve availability values that closely meet availability requirements and maintained low cost. For both configurations Telco's availability is the main driver of the overall availability. In a radio site architecture where only one Telco components is used, the overall availability is always lower than the availability of the component with the lowest availability value (i.e., Telco 0.9979). A parallel Telco component is added in both main and backup radio site architecture, in order to improve overall availability. The price paid is the cost of an additional leased telecommunication service (Telco.) figure E–78 shows the radio site configuration and RMA analysis where the main radio is used.

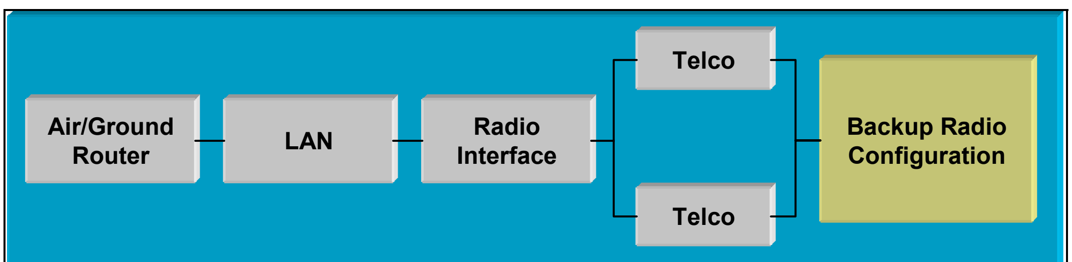
Figure E–79 shows the radio site configuration and RMA analysis where the backup radio is used.



RMA Analysis

	MTBF (hrs)	MTTR (hrs)	Availability
Air/Ground Router	60000	0.5	0.999991667
LAN	50000	0.5	0.999990000
Radio Interface	40000	0.5	0.999987500
Telco			0.997900000
Telco			0.997900000
Main Radio			0.999984425
			0.999949183

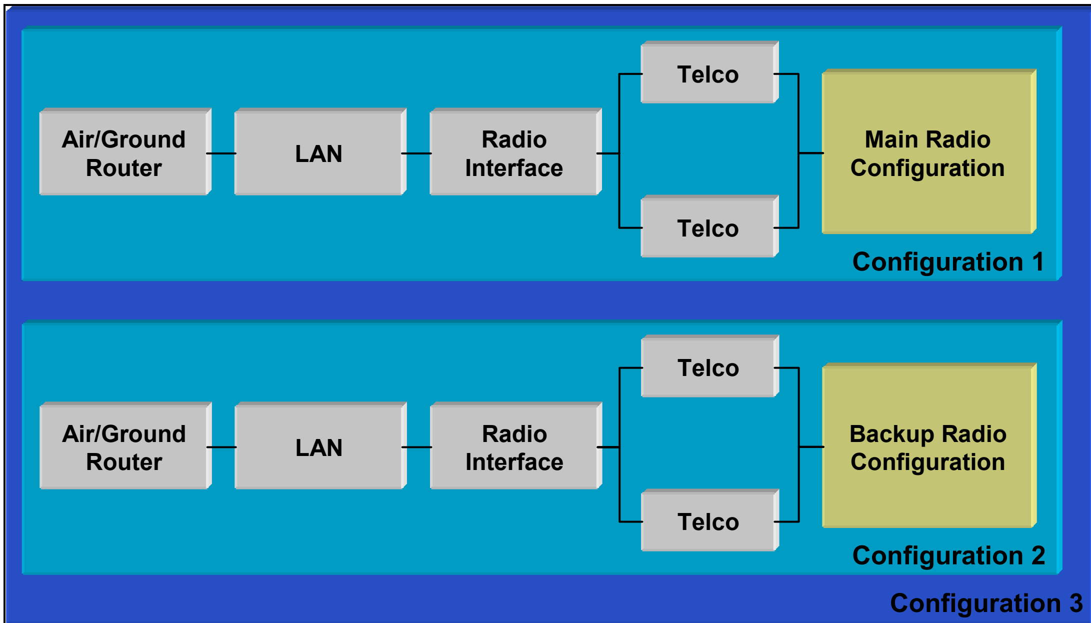
Figure E–78.—Radio Site Configuration With Main Radio Element.



RMA Analysis

	MTBF (hrs)	MTTR (hrs)	Availability
Air/Ground Router	60000	0.5	0.999991667
LAN	50000	0.5	0.999990000
Radio Interface	40000	0.5	0.999987500
Telco			0.997900000
Telco			0.997900000
Backup Radio			0.999870666
			0.999835428

Figure E–79.—Radio Site Configuration With Backup Radio Element.



RMA Analysis

	Availability
Configuration 1	0.999949183
Configuration 2	0.999835428
	0.999999992

Figure E–80.—Radio Site Configuration That Meets COCR Availability Requirements.

Both these radio site configurations are valid configurations, but they do not meet the COCR Phase II enroute availability of provision requirements of 0.99999995. To achieve this stringent availability number, parallel radio site architecture is needed. The architecture and RMA analysis of the radio site configuration that meets COCR availability are shown on figure E–80. This architecture availability meets COCR requirements (1 to 8.0×10^{-9} > 1 to 5.0×10^{-8}) and was used to derive required equipments for cost analysis.

E.1.8.3 Cost estimating

The L-Band cost estimating process was based on NASA cost estimating handbook. The cost estimating process starts with development of rules and assumptions. It continues with cost methodology selection, the construction of cost model, and the gathering of data. The final step on this process is development of estimate where the gathered data is entered into the cost model, which provides the output. Figure E–81 shows the L-Band cost estimating process.

The development of rules and assumptions is a very important step of the cost estimating process. One of the subtasks of the development of rules and assumptions step is defining the scope of estimate. Because of the depth of this study the focus is only on the cost estimation of the most important elements of L-Band system. The FAA elements of the Life Cycle Cost (LCC) model are the pool of cost elements from which cost elements were selected for further in-depth analysis. The FAA's LCC model elements and the elements selected for analysis are shown in figure E–82.

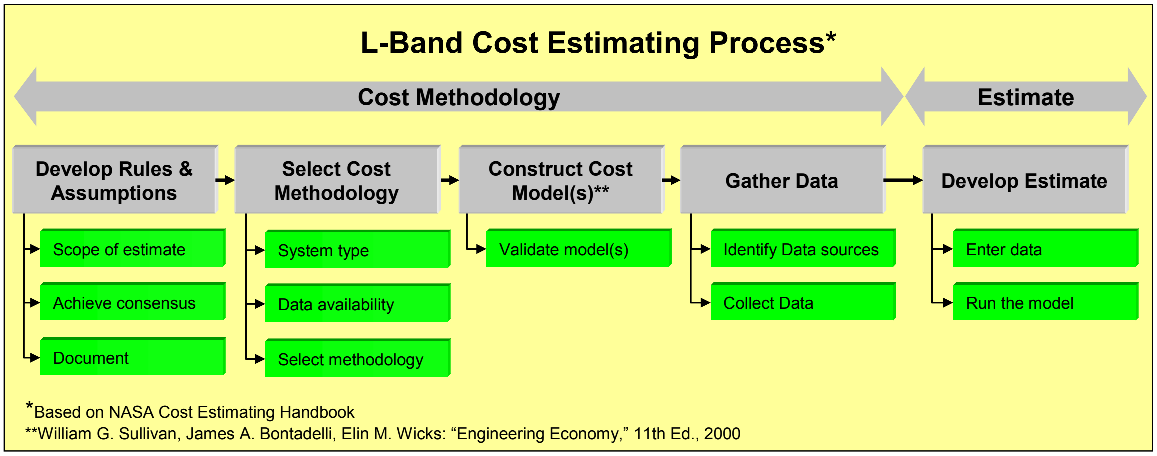


Figure E–81.—L-Band Cost Estimating Process.

FAA LCC Model (all elements)

Research and Development
- Feasibility Analysis
- Environmental Assessment
- Prototype Hardware
- Test Facilities
- Technical Experiments
- Operational Tests
- Construction Project Design and Engineering Plans
- Coordination with Regional Development and Transportation Plans
- System Design and Engineering
- R&D Oriented Software
- Modeling and Simulation
- Regulatory Analysis (prior to issuance of a final regulation)
- Arrangement of Project Financing
- Public Outreach

Investment
- Land
- Facilities
- Equipment
- Other regulatory implementation costs
- Transition costs.

Operations and Maintenance
- Personnel Costs
- Consumables
- Energy and Utilities
- Facilities
- Telecommunications
- Computer Service Costs:
- Spares and Support Equipment
- Packaging, Handling, and Transportation
- Recurring Training
- Recurring Travel

Termination
- Dismantling Costs
- Transportation and Packaging
- Site Restoration
- Storage of Material Management
- Salvage Value (offset to termination costs)

FAA LCC Model Elements Selected for Analysis

Research and Development
- System Design and Engineering
- Modeling and Simulation
- Other costs

Investment
- Facilities
- Equipment
- Other regulatory implementation costs

Operations and Maintenance
- Telecommunications
- Other costs

Figure E–82.—Scope of Estimate.

The cost elements selected for in-depth analysis are:

- Research and Development
    - System Design and Engineering
    - Modeling and Simulation
    - Other costs
- Investment
    - Facilities
    - Equipment
    - Other regulatory implementation costs
- Operations and Maintenance
    - Telecommunications
    - Other costs (personnel, etc.)

In addition, three important assumptions and/or observations are worth emphasizing:

- L-Band system provides coverage to Unites States, including Alaska and Hawaii
- Coverage is above FL 180
- System Availability of Provision meets COCR requirements for Phase II en route services

The next step in the cost-estimating process is to identify and select the cost methodology to be used. The objective of the cost model is to evaluate the economic profitability and liquidity of the single proposed solution for the L-Band coverage. Measures of a project's profitability

- Present Worth (PW)
- Future Worth (FW)
- Annual Worth (AW)

All measures are essentially equivalent; they differ in their time reference. Measures of a project's liquidity:

- PW Simple Payback Method
- FW Discounted Payback Method
- AW Investment Balance

Each of these models provides the same "answer." They differ in their frame of reference. The "PW Simple Payback Method" was selected as the methodology for cost-estimating model. This model compares current costs to discounted future returns (and discounted future costs) and the "answer" is in today's dollars.

There are several elements of the PW Simple Payback model. The most important ones are listed below:

- Capital Investment
- Annual Revenue
- Annual Expenses
- Minimum Attractive Rate of Return (MARR)

MARR is an interest rate used to convert cash flows into equivalent worth at some point in time. For the PW Simple Payback model, the “point of time” is the present. MARR is usually an organizational policy issue based on amount, source, and cost of money available for investment, amount of perceived risk of investment opportunities, estimated cost of administering projects over short and long run, and type of organization involved. Other factors influence the perceived value of MARR.

A typical range of MARR is between 5 and 25%. For the initial L-Band cost model analysis, the selected MARR was 5% because the project is viewed as low risk and without significant initial investment required.

PW Simple Payback Method model indicates liquidity rather than profitability of the project. The question that was posed is, “In a given timeframe, what is the minimum annual revenue required for the capital investment recovery?” Usually this type of investment demands relatively short time for capital investment recovery to be attractive to investment community. A 4-year timeframe was selected. The following inequality formula is the bases of the PW Simple Payback Method model

$$\sum_{k=1}^{4}\left(AR_k - AE_k\right)\left(P/F,i,k\right) - I \geq 0$$

where

AR_k is annual revenue in year k (this is the unknown)
AE_k is annual expenses in year k
I is the capital investment made at the present time
i is the interest rate equal to MARR

The next step in the cost-estimating process is to gather data to be used in the PW Simple Payback Method model. An estimate for radio sites was developed by generating a manifest of typical radio site components by analogy to existing infrastructure. Construction costs was also estimated by analogy and the demarcation between construction and equipment costs was somewhat arbitrary. The following were defined as the typical radio site components that would be provided by “site construction”:

- Freestanding steel antenna support towers (typically 50 to 70 feet high and typically four per site)
- Equipment building (concrete masonry or prefabricated poured concrete)
- Access road and parking turn-a-round area
- Underground radiofrequency (RF) and power cables
- Grounding and lightning protection system
- Perimeter fence
- Engine generator
- Fuel storage tank

A notional radio site architecture is shown in figure E–83.

Construction costs were estimated by searching FAA contract opportunities for contracts. The DTFA14-02-R-34237 synopsis cites FAA contract offer range of $500,000 to $750,000 for Indianapolis International Airport RCAG site construction. Because of the location of this radio site (on an airport), the contract price is higher than the average. For this analysis, the average radio facility cost should be close to the low-bound contract range. A value of $500,000 was selected as the average facility construction cost.

The equipment costs for the radio site are derived for the architecture of the radio site. Figure E–84 shows the equipment of the radio site as derived from the availability analysis.

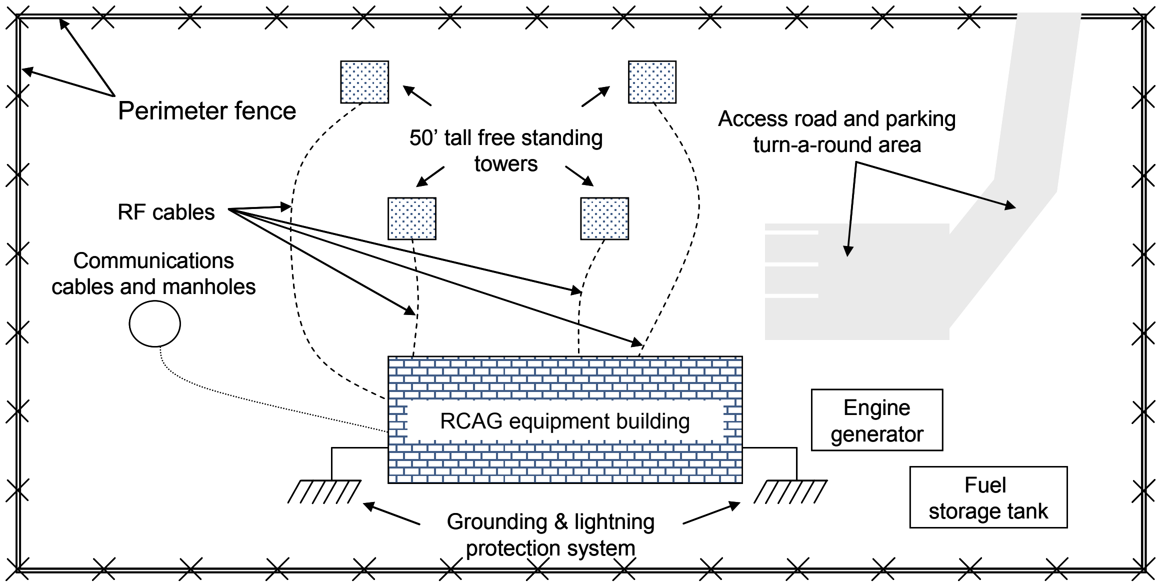


Figure E–83.—Notional Radio Site Architecture.

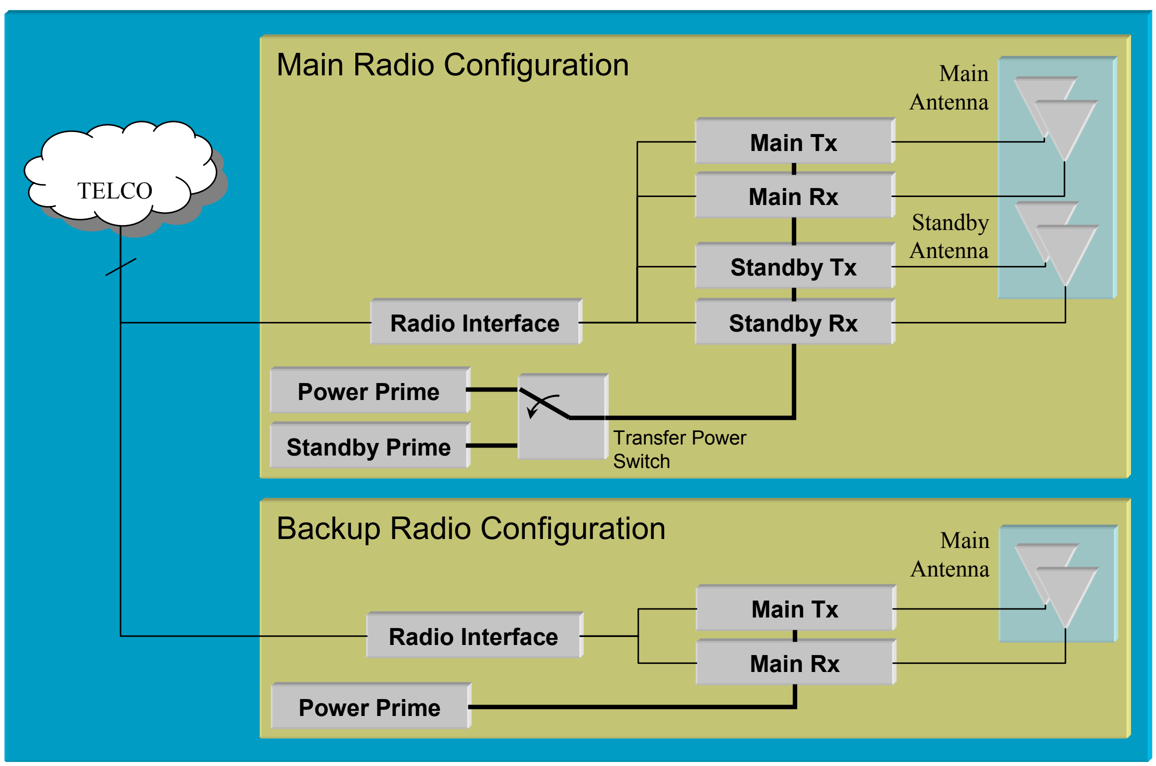


Figure E–84.—Notional Radio Site Equipment Configuration Used To Develop Equipment Cost Estimate.

Estimated cost for radio equipment was taken from previous cost-estimation work for VHF radio equipment. The estimated cost for L-Band receiver/transmitter (Rx/Tx) was considered to be twice the cost of a VHF Rx/Tx since, in today's market, the selection of L-Band Rx/Tx is more limited. Based on the "First Order Analysis of Required Bandwidth for the Next-Generation Aeronautical Data Link" paper, the radio site may need more than one frequency to meet data rate requirements. The increased number of required frequencies per radio site linearly increases the equipment needed such as receivers, transmitters, and equipment racks. The average number of frequencies required per radio site is 2.29 for the base rate of 100 kbps. Four items (transmitter, receiver, antenna, and equipment rack) include multiplication by 2.29 to account for additional hardware due to the number of frequencies required. Table E–10 shows the derivation of the average equipment cost for the radio site.

TABLE E–10.—AVERAGE EQUIPMENT COSTS PER RATIO SITE

Main Radio Cost				2.29
Item	**Description**	**Estimated Cost**	**Quantity/Freq**	**Total Cost**
Transmitter	L-Band Transmitter	$10,000.00	2	$45,800.00
Receiver	L-Band Receiver	$10,000.00	2	$45,800.00
Antenna	L-Band Antenna	$2,832.00	4	$25,941.12
UPS	Uninterruptible Power Supply	$6,975.00	2	$13,950.00
Radio Interface	Remote Radio Control Equipment	$2,500.00	1	$2,500.00
Cables and Connectors	Various	$5,000.00	1	$11,450.00
Equipment Rack	Equipment Racks	$1,150.35	2	$5,268.60
Transfer Power Switch	Automatic power switch transfer	$1,500.00	1	$1,500.00
32 kW Diesel Generator	Diesel Generator	$9,200.00	1	$9,200.00
				$161,409.72
Backup Radio Cost				
Item	**Description**	**Estimated Cost**	**Quantity/Freq**	**Total Cost**
Transmitter	L-Band Transmitter	$10,000.00	1	$22,900.00
Receiver	L-Band Receiver	$10,000.00	1	$22,900.00
Antenna	L-Band Antenna	$2,832.00	2	$12,970.56
UPS	Uninterruptible Power Supply	$6,975.00	1	$6,975.00
Radio Interface	Remote Radio Control Equipment	$2,500.00	1	$2,500.00
Cables and Connectors	Various	$5,000.00	1	$11,450.00
Equipment Rack	Equipment Racks	$1,150.35	1	$1,150.35
Transfer Power Switch	Automatic power switch transfer	$1,500.00	1	$1,500.00
32 kW Diesel Generator	Diesel Generator	$9,200.00	1	$9,200.00
				$91,545.91
		Average equipment cost per radio site		**$126,477.82**

For O&M costs, the Safe Flight 21-CBA Basis of Estimates April 2001 document was used to derive several O&M cost aspects for L-Band radio sites. SF21 Basis of Estimates document provides among other estimates the ADS-B link NAS-Wide en route O&M cost detail. This cost is divided in 5 main cost elements

- Site Maintenance
- Program Support
- Logistics
- Second-Level Engineering
- Infrastructure Support (dominated by Leased Telecommunications costs)

For the first four elements, it can be concluded that both ADS-B and L-Band radio sites incur similar O&M costs. This is because both systems perform similar functions, include comparable number of equipment in their inventories, and require similar staffing and maintenance to achieve system availability requirements. Table E–11 shows the derivation of the L-Band O&M cost without taking into account the Infrastructure Support element.

TABLE E–11.—L-BAND O&M COSTS (PARTIAL)

L-Band O&M cost derivation	O&M ADS-B Total 28 years	O&M ADS-B Total/year	O&M ADS-B Total/year/radio site	O&M L-Band 132 radio sites Total/year
Total Site Maintenance (PM+CM)	$16,726,900.00	$597,389.29	$5,973.89	$788,554
Program Support	$2,742,100.00	$97,932.14	$979.32	$129,270
Logistics	$28,996,500.00	$1,035,589.29	$10,355.89	$1,366,978
Second Level Engineering	$21,316,000.00	$761,285.71	$7,612.86	$1,004,897
				$3,289,699.29

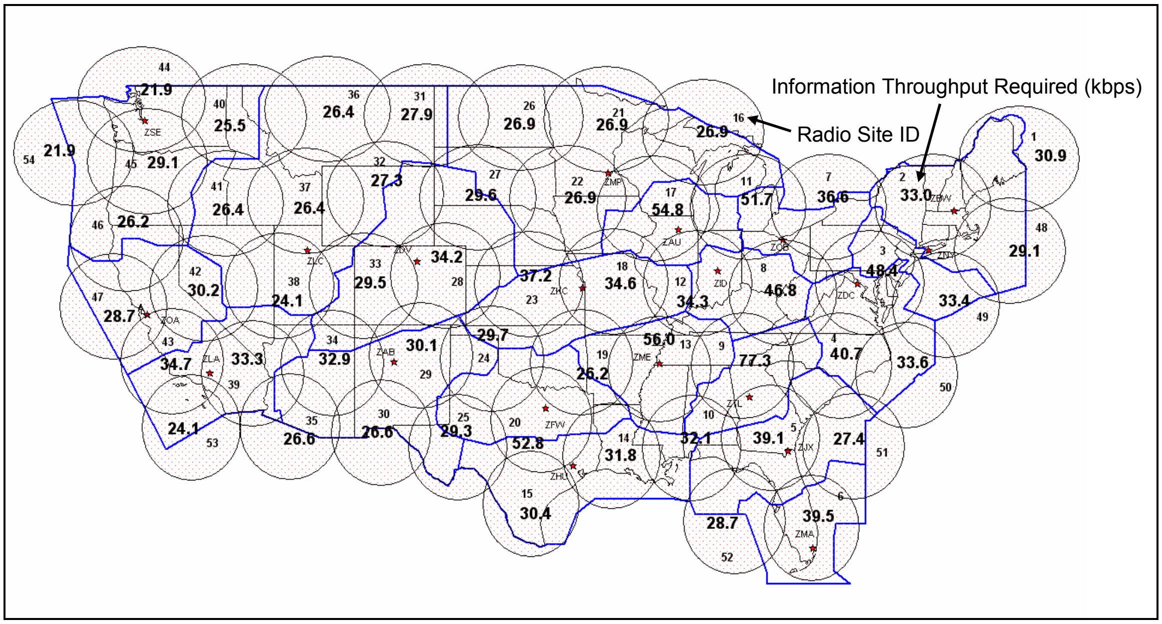


Figure E–85.—Information Throughput Required.

For the leased telecommunications, O&M costs are expected to differ significantly since the L-Band data requirements per radio site is much lower than the ADS-B link data requirements. Calculations for the Leased Telecommunications O&M costs were based on the “First Order Analysis of Required Bandwidth for the Next-Generation Aeronautical Data Link” paper. Analysis does not include Alaska and Hawaii. An assumption was made to use 22.2 kbps for all radio sites located in Alaska and Hawaii. The information throughput required for each radio site is used to calculate the number of DS0 (56 kbps) lines needed to support the required data rate. The figure E–85 shows the information throughput required in kbps for each radio site.

Based on the above map, most radio sites require only one DS0 line, but two radio sites (ID9, 77.3 kbps and ID13, 56 kbps) require two DS0 lines. Main and backup radios needed for Telco redundancy would require twice the number of DS0 lines. Table E–12 shows the calculation used to derive the total number of DS0 lines for all radio sites and the associated yearly cost.

TABLE E–12.—TOTAL REQUIRED DS0 LINES

L-Band O&M cost derivation	<56kbps	>56kbps	Required redundancy	DSO lines
Main radios	64	2	2	136
Backup radios	64	2	2	136
Total DSO lines				272
DSO monthly charge				$250.00
Leased Telecommunications yearly cost				$816,000.00

Table E–13 shows the cost estimation of all five elements of O&M yearly cost for the L-Band architecture.

TABLE E–13.—ESTIMATED O&M COSTS

L-Band O&M cost derivation	O&M L-Band 132 radio sites Total/year
Total Site Maintenance (PM+CM)	$788,554
Program Support	$129,270
Logistics	$1,366,978
Second Level Engineering	$1,004,897
Leased Telecommunications	$816,000.00
	$4,105,699.29

The Research and Development cost was estimated at $20,000,000.00 by analogy with NEXCOM project. Table E–14 shows the Initial Investment and O&M estimated costs summary.

TABLE E–14.—INITIAL INVESTMENT AND O&M COSTS SUMMARY

FAA LCC Model Elements	
Research and Development	**$20,000,000.00**
System Design and Engineering	$10,000,000.00
Modeling and Simulation	$6,000,000.00
Other costs	$4,000,000.00
Investment	**$114,695,071.78**
Cost for all Radio Sites (equipment, construction, facilities)	$82,695,071.78
Other Facilities (3 POP)	$30,000,000.00
Other regulatory implementation costs	$2,000,000.00
Initial Investment	**$134,695,071.78**
Operations and Maintenance	**$4,105,699.29**
Telecommunications	$816,000.00
Other costs	$3,289,699.29
O&M	**$4,105,699.29**

The initial investment for the L-Band system was estimated to be $134,695,071.78 with corresponding O&M of $4,105,699.29. The O&M estimation is the yearly annual expenses that the L-Band system would incur during 4 years timeframe required for the recovery of the initial investment. The data on the above table was used as the input to the PW Simple Payback Method model to derive the required annual revenue needed to close the business case in a 4-year timeframe. Table E–15 shows the model input and output results.

TABLE E–15.—PW SIMPLE PAYBACK METHOD MODEL

Inputs		
Initial investment		-$134,695,071.78
Annual Expenses		-$4,105,699.29
Years		4
MARR		5%
Output		
Annual Revenue		$42,091,303.32
Investment Balance **($1000)**		
	Start of period	End of period
(I)	$0.00	-$134,695.07
1	-$141,429.83	-$103,444.22
2	-$108,616.43	-$70,630.83
3	-$74,162.37	-$36,176.77
4	-$37,985.60	$0.00

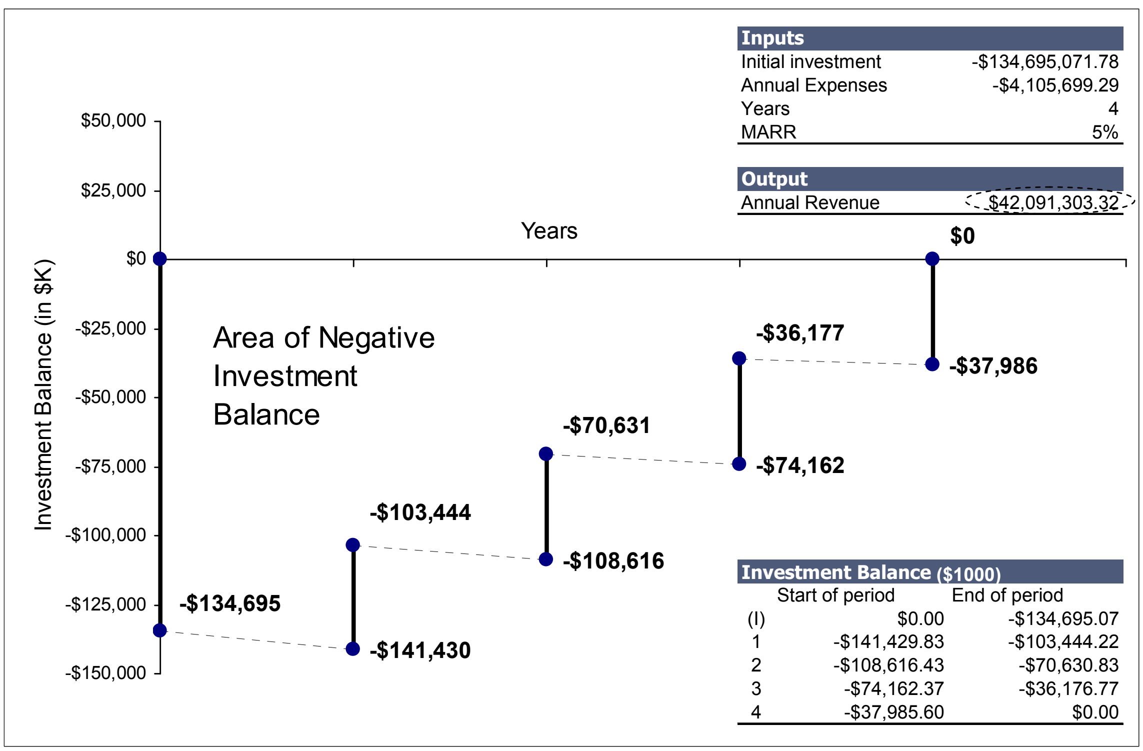


Figure E–86.—Graphical Representation of PW Simple Payback Method.

Figure E–86 is a graphical representation of the PW Simple Payback Method model as it applies to the L-Band system. The required annual revenue to close the business case was estimated to be $42,091,303.32.

E.2 SATCOM Environment and Applicable Technology Analysis

For the Satellite and Over Horizon technology family, two technology inventory candidates have emerged from the technology screening: Inmarsat SBB and Custom Satellite Solution. The Inmarsat SBB candidate differs from many of the other candidates considered in that it is an operational system with a defined service architecture and a defined set of service offerings. For this candidate, the ability to meet COCR performance requirements was selected as the focus of detailed analysis.

COCR performance requirements are specified for data capacity, latency, QoS, and maximum number of users, but there are also availability and integrity requirements for aeronautical services. The performance of Inmarsat SBB with regard to capacity, latency, QoS, and number of users was evaluated as part of the initial iteration of AHP step 6 along with other screened technologies. This being the case, the selected focus for the detailed analysis was other COCR performance requirements, specifically availability performance. Availability was selected as it was considered as a potential shortfall of the satellite candidate solutions.

The Custom Satellite Solution is a technology concept that includes the fielding of a custom satellite or custom satellite payload specifically designed for aeronautical communications. This concept is being explored by several civil aviation authorities and related organizations. Japan has launched an aeronautical communication satellite and is exploring performance of next-generation satellite systems. The Global Communication, Navigation, & Surveillance System (CGNSS) contract COCR Phase 1 study explored the definition of a satellite architecture for providing aeronautical safety services. Finally, there are consortiums that are working to define aeronautical satellite specifications, such as the Satellite Data Link System (SDLS). Within this body of work, the need to accommodate all communication safety services with associated performance requirements has been considered. It has been found that to meet these requirements, a highly reliable, highly available architecture is required, such as the five satellite architecture proposed in the GCNSS study.

Here again, availability arises as an important issue. In order to provide required availability, a highly redundant custom satellite system architecture is needed. As this issue is similar to that noted above for Inmarsat, a separate study of availability for Custom Satellite Solutions was not performed. Rather, it was considered to be more instructive to estimate the availability of two existing, operational satellite systems, Inmarsat SBB and Iridium that provide services in protected aeronautical spectrum (AMS(R)S).

In summary, the focus of the detailed analysis for satellite technologies was availability performance. The performance of existing AMS(R)S systems (namely Inmarsat SBB and Iridium) was examined. Based on the study results, recommendations to be considered for evaluation of the Inmarsat SBB and Custom Satellite Solution technology candidates in support of AHP steps 6 and 8 were made.

The satellite detailed analysis was organized into two major task activities. The first was an architecture-specific availability assessment. The second was the evaluation of COCR service provisioning given the availability assessment results. Evaluation of hybrid satellite architectures and drawing conclusions supporting technology assessment were also addressed. Specific work items of this study are documented in the following sections:

- Section E.2.1—Satellite Communication Availability Analysis
- Section E.2.2—COCR Service Provisioning Using Satellite Communications
- Section E.2.3—Hybrid Satellite Communication Architectures
- Section E.2.4—Summary and Recommendations

E.2.1 Satellite communication availability analysis

This study examines the availability performance of Inmarsat SBB and Iridium (two current satellite service offerings in AMS(R)S spectrum) and provides a high-level comparative analysis of the calculated performance to a representative VHF terrestrial data communication architecture.

E.2.1.1 Introductory material

E.2.1.1.1 Identification of architectures for analysis

As means of an introduction, a brief overview of both the Inmarsat SBB and Iridium services and architectures is provided.

Inmarsat SBB is a fourth-generation service offering of Inmarsat. It includes two I-4 geostationary satellites (positioned over the Atlantic and Indian Oceans) with the potential to include a third satellite over the Pacific Ocean (although this third satellite may remain as a ground spare for the first two spacecraft). A depiction of the proposed coverage of the SBB satellites and associated spot-beams is provided in figure E–87.

The SBB services include both circuit and packet switch connections, including a guaranteed “streaming” data service. The ground infrastructure is European based including a satellite access station (SAS) in Berum, Belgium and Fucino, Italy. The ground infrastructure includes internal routing between these SAS sites to accommodate re-routing of traffic in the event of a SAS gateway failure. A depiction of the Inmarsat SBB ground infrastructure is provided in figure E–88.

To support the availability analysis, overall availability performance, as well as performance specific to a representative region of the U.S. National Airspace System (NAS), was considered. The geographic region associated with three Air Route Traffic Control Centers (ARTCCs) was selected as this representative region. These areas encompassed the Memphis (ZME), Atlanta (ZTL), and Indianapolis (ZID) ARTCC regions. A view of Inmarsat SBB spotbeam coverage of the representative NAS region is shown in figure E–89.

Iridium is a second AMS(R)S system that offers two-way global voice and data aeronautical communication services. The Iridium architecture consists of 66 fully operational satellites and 11 in-orbit spares. Its full constellation life is designed to last through mid-2014 with plans in place to extend the constellation to beyond 2020. The satellites are organized into six planes of near-polar orbit, where each satellite circles the Earth every 100 minutes. Iridium offers full-duplex 2400-bps user channels for provision of voice and data services.

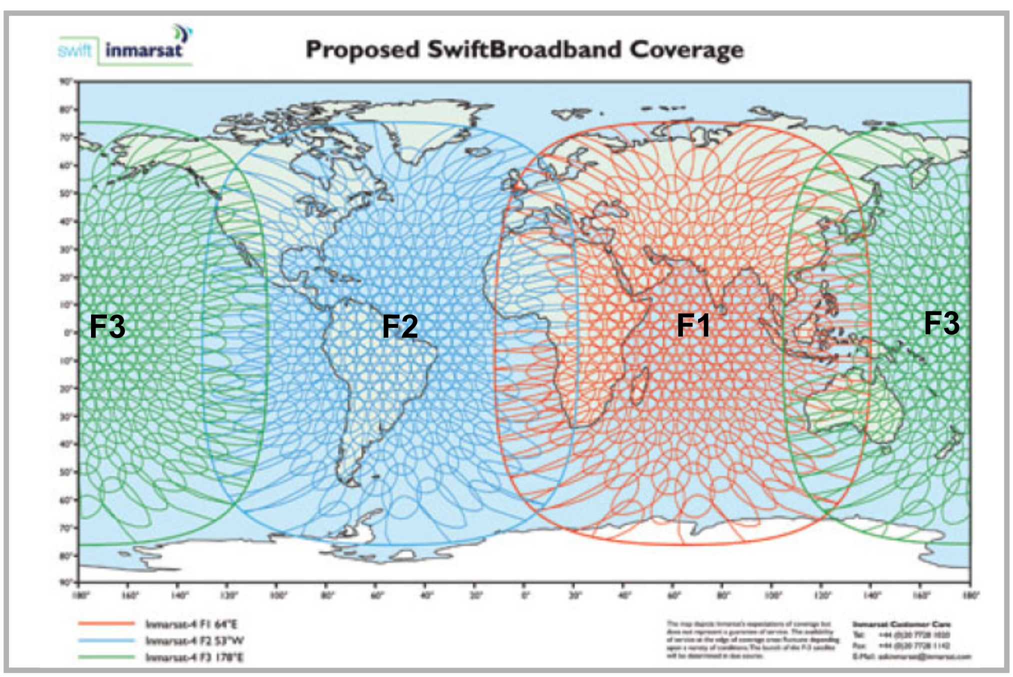


Figure E–87.—Proposed Inmarsat SBB Coverage.

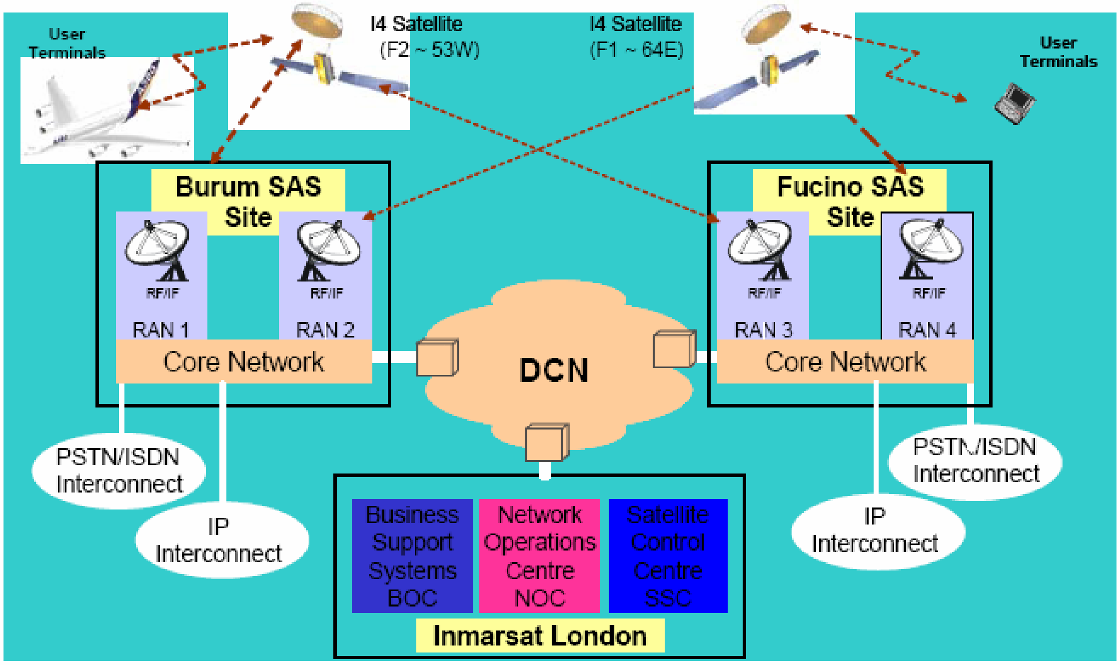


Figure E–88.—SBB Ground Infrastructure.

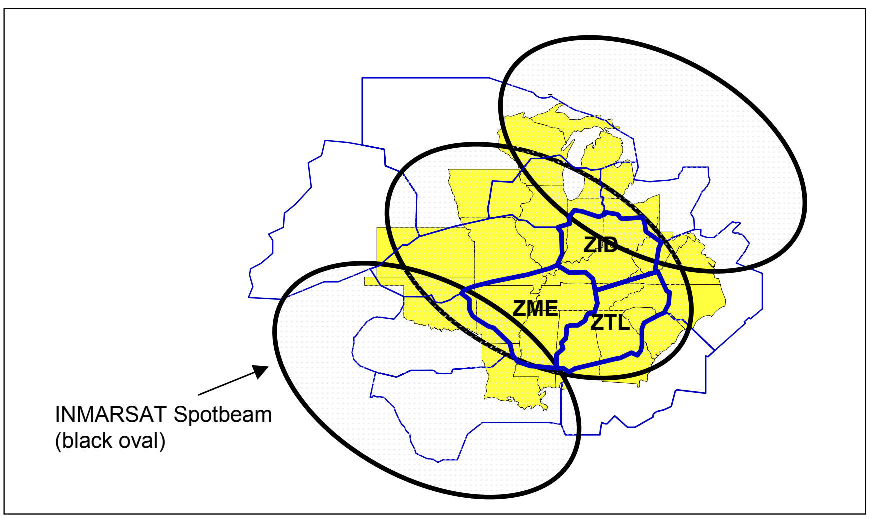


Figure E–89.—Inmarsat SBB Spotbeam Coverage of Representative NAS ARTCCs.

The Iridium ground infrastructure includes a single aeronautical gateway and a main and backup satellite network operation center (primary in Landsdown, VA; backup in Chandler, AZ). An overview of the Iridium architecture supporting aeronautical applications is provided in figure E–90.

A representative view of Iridium coverage of the NAS reference region is provided in figure E–91. In this figure, a portion of the NAS reference area falls within view of two Iridium orbital planes (approx. 20% of the reference region).

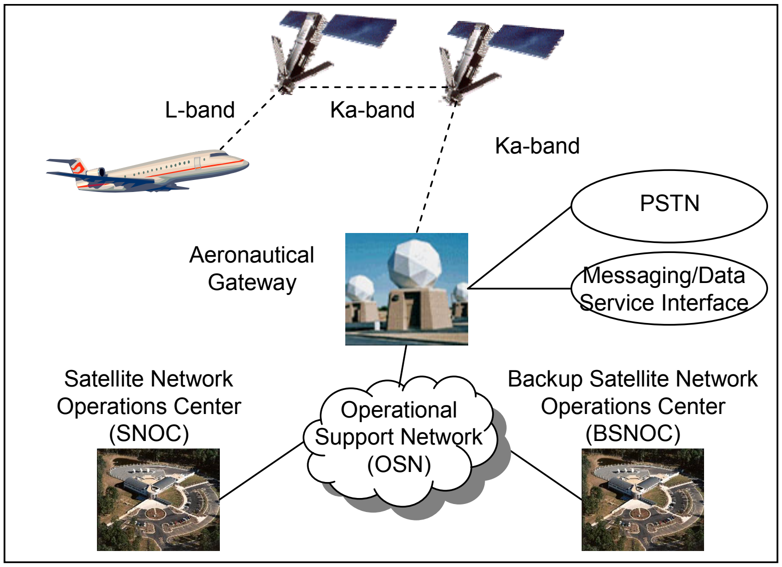


Figure E–90.—Iridium Aeronautical Architecture.

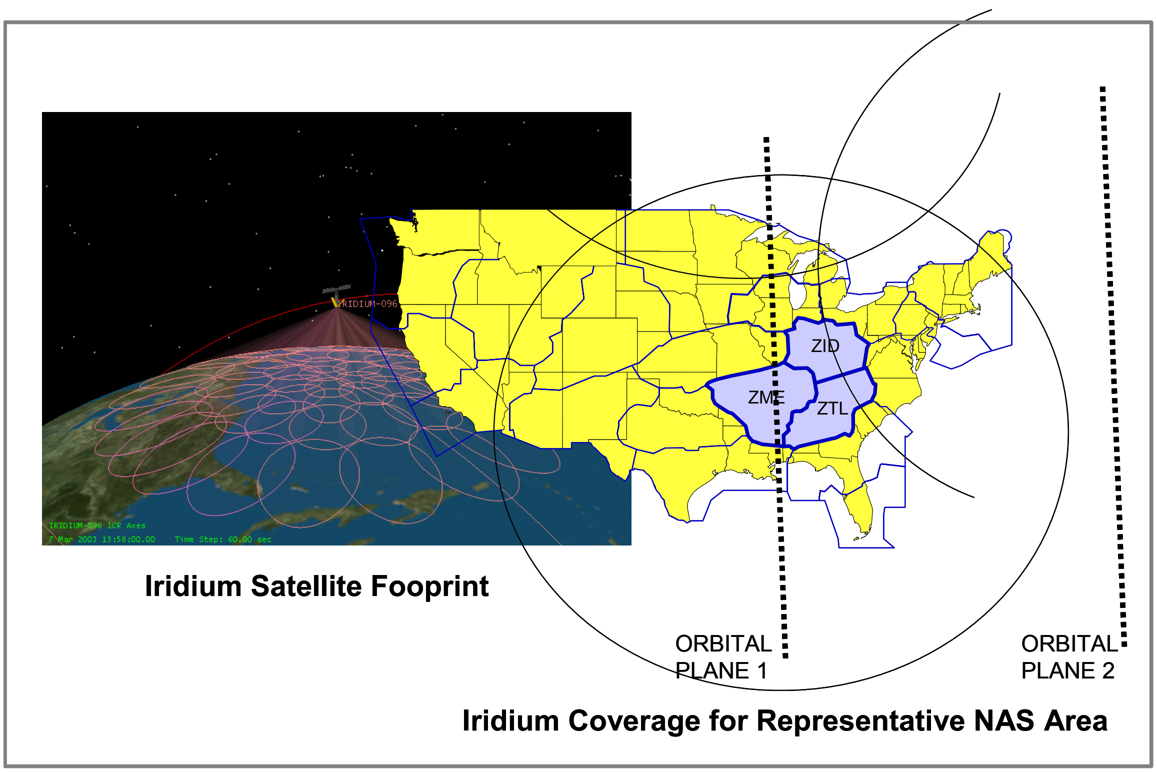


Figure E–91.—Iridium Coverage of Representative NAS ARTCCs.

E.2.1.1.2 Definitions, Assumptions, and Approach

This section focuses on the analysis definitions, assumptions and study approach for this detailed analysis. first, consideration is given to the definition of availability. given that link interruptions and system component failures can lead to service outages, and each outage requires varying restoration times, it can be seen that availability characterizes the impact of interruptions, failures and service restoration times on the usability of a system. in other words, it is the percentage of time a system is available for use. availability can generally be described as the following ratio:

$$\frac{\textbf{(Observation Time – Total Outage Time)}}{\textbf{Observation Time}}$$

To apply the ratio above, a definition of "Outage Time" is needed. Typically, an outage is defined as the time the service is not meeting a specified performance or QoS. For a data service, this is often described as a service providing a certain BER while meeting maximum latencies.

RTCA has published a standard that specifically addresses the specification of satellite performance for provision of AMS(R)S aeronautical data links. This document, *Document Order 270 (DO-270) MASPS for the AMS(R)S as Used in Aeronautical Data Links*, includes definitions, formulas, and approaches specific to the study of satellite availability performance. This document organizes system outages into two general categories:

- Multi-User Service Outage: a service outage simultaneously affecting multiple aircraft within a defined service volume
- Single-User Service Outage: a service outage affecting any single user aircraft within a defined service volume

The focus of the current study is service provisioning for multiple aircraft within a defined service volume, that is, multi-user service outages.

If a system covers a large region of airspace and if partial outages could occur, then a geographically dependent availability ratio should be used. This was applied in some cases of the current analysis. The applicable formula, as defined in DO-270, is provided in figure E–92:

With availability defined, the next step was to define an approach for evaluating availability performance of the satellite architectures of interest. Specifically, a satellite communication (SATCOM) availability analysis model described in RTCA DO-270 was applied. This model defines an availability fault-tree to permit individual characterization and evaluation of multiple availability elements. The model, which includes system component failures and fault-free event failures, is shown in figure E–93.

$$\overline{A(T_{OBS})} = \int_{\Omega} \left[1 - \frac{\sum_k (T_{OUT}(\vec{x}))_k}{T_{OBS}} \right] p_{\vec{x}}(\vec{x}) d\vec{x}$$

$$= \int_{\Omega} 1 \times p_{\vec{x}}(\vec{x}) d\vec{x} - \int_{\Omega} \frac{\sum_k (T_{OUT}(\vec{x}))_k}{T_{OBS}} p_{\vec{x}}(\vec{x}) d\vec{x}$$

$$= 1 - \frac{1}{T_{OBS}} \int_{\Omega} \left[\sum_k (T_{OUT}(\vec{x}))_k \right] p_{\vec{x}}(\vec{x}) d\vec{x}$$

Note:

T_{OBS} = Observation Time

T_{OUT} = Outage Duration

$\vec{X}$ = Observation Location

$P_{\vec{x}}(\vec{x})$ = Probability density function of users over the coverage volume Ω

Figure E–92.—Geographically Dependent Availability Calculation.

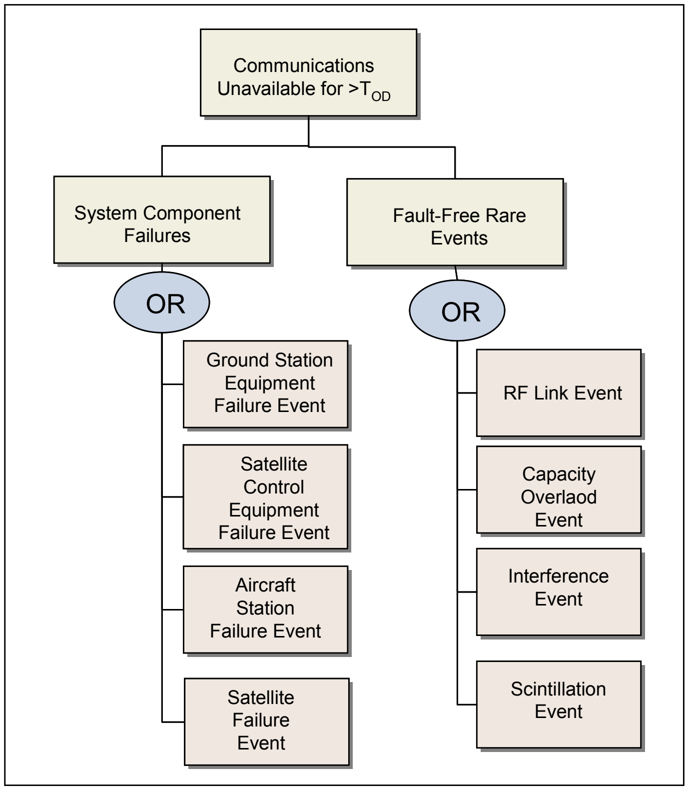


Figure E–93.—Availability Fault Tree.

When a complex system consists of independent serial elements, the overall availability is equal to the product of the availability ratios for the individual elements. That is,

$$A_{oSYS} = A_{o1} \times A_{o2} \times A_{o3} \times \ldots \times A_{oN}$$

This can be applied to the availability tree model to characterize an overall architecture availability with a single number and is the approach presented in DO-270. However, this approach has limitations including:

- The independence assumption is not always valid
- Reducing this complex model into a single number oversimplifies the issue
- "Tall poles in the tent" in a multiplicative relation dominate the entire product
- Observation time periods may be different for different elements
- This approach is risky when one or more of the element availability calculations are based on incomplete or "similar in kind" data, as in this case

Due to these limitations, this approach was not used for this study. Instead, availability was assessed for each availability element, including both system component availability elements and fault-free event availability elements. These findings were then compared and contrasted for the two SATCOM architectures, as well as for a notional terrestrial VHF A/G communications architecture.

E.2.1.2 Availability calculations

To ensure a clear understanding of analyzed architecture components, the role of the FRS (as specified by the COCR) was defined in the context of the standard Aeronautical Mobile Satellite System (AMSS) model. This is shown visually in figure E–94.

In figure E–94, the FRS includes the system components encompassed by Points B through C. To determine what this means in terms of the Inmarsat SBB and Iridium architectures, a block diagram of considered architecture components was developed. The block diagram of modeled Inmarsat SBB is provided in figure E–95.

Associated with the Inmarsat SBB block diagram are several assumptions. First, it was assumed that the NAS is serviced by a single I-4 satellite with a ground spare available for backup in the case of unrecoverable spacecraft failure. Also, it was assumed that users can be accommodated by either SAS, and Inmarsat offers a fully redundant Network Operations Center (NOC).

The modeled Iridium architecture is shown in figure E–96.

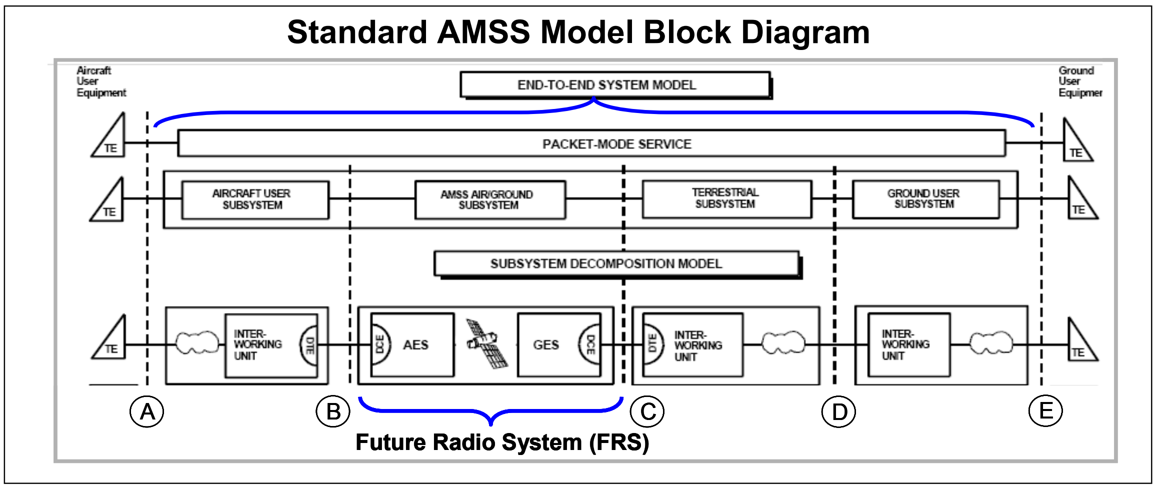


Figure E–94.—FRS in the Context of the AMSS Model.

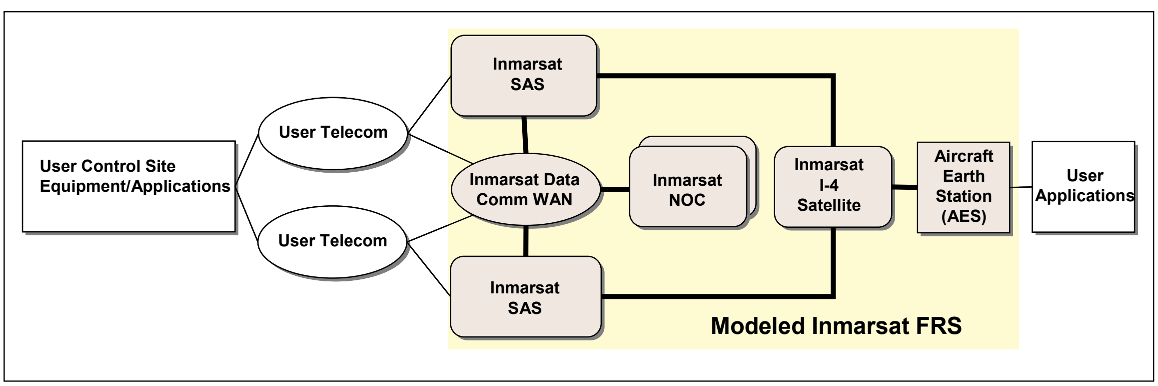


Figure E–95.—Inmarsat SBB Modeled Architecture.

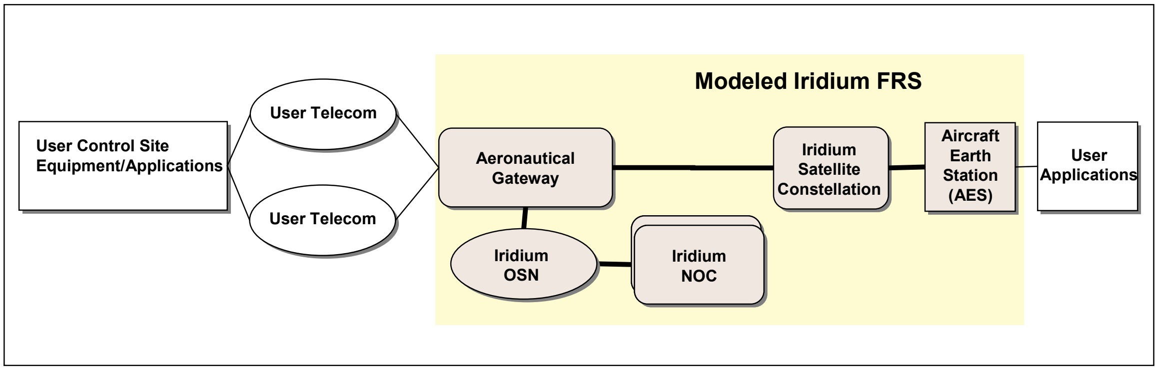


Figure E–96.—Iridium Modeled Architecture.

Here, the NAS is assumed to be serviced by either one or two Iridium orbital planes and an assumption that Iridium offers a fully redundant NOC is made.

E.2.1.2.1 System failure components

System component availability calculations were based on the FRS component failure model elements, as shown on the left branch of the availability tree model. These components are analyzed in the following sections:

- Ground Station Equipment—Section E.2.1.2.1.1
- Satellite Control Equipment—Section E.2.1.2.1.2
- Aircraft Station Equipment—Section E.2.1.2.1.3
- Satellite Spacecraft—Section E.2.1.2.1.4

E.2.1.2.1.1 Ground Station Equipment

For satellite systems, ground station equipment failure events are failures associated with its Ground Earth Station(s) (GESs) and any terrestrial networking between the GESs (if more than one is available). Specific components considered for Inmarsat SBB and Iridium FRS components are shown in figure E–97.

In calculating availability for ground Earth station equipment, redundancy and load sharing was accounted for. For Iridium, this was not a factor as there is a single, nonredundant ground station servicing users. For Inmarsat, redundancy was provided and accommodated in the availability analysis. The formula used for calculation of ground station availability was as follows: $A_{KI} = 1\text{-}(1\text{-}A_{GS})^K$ where K is the number of redundant elements; A_{KI} is availability for K redundancy with independent repair; and A_{GS} is availability of a single ground station component. For Iridium, K = 1 while for Inmarsat SBB, K = 2.

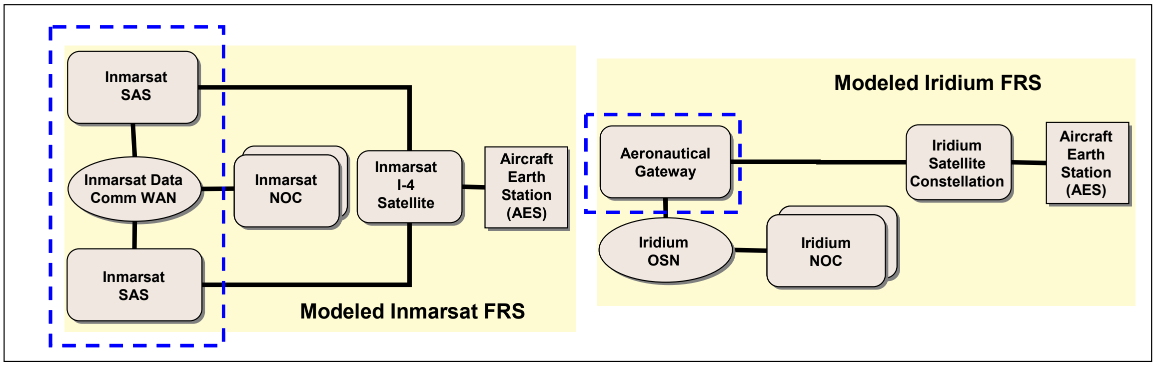


Figure E–97.—Modeled Ground Station Components.

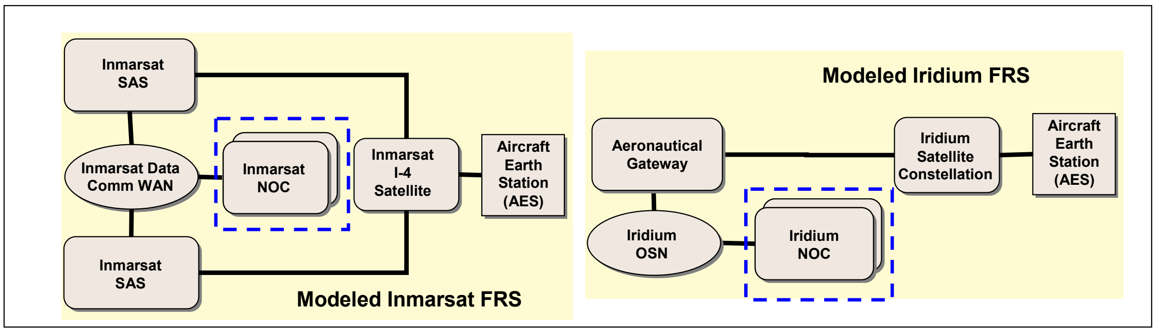


Figure E–98.—Modeled Ground Control Components.

For these architectures, specific ground system outage data was not available from Inmarsat or Iridium. Instead, available GES outage information was used to derive "similar in kind" assumptions applied to both SATCOM architectures. Historical data reviewed included Inmarsat F2/F3 older ground station data (from 2004), which included a small number of individual outages ranging from 5 to 16 minutes in duration. Applying conservative assumptions, a failure rate of once per year with outage duration of 15 minutes was estimated for this analysis. Applying the formula above (with availability calculated over an observation period of 1 year or 8766 minutes) resulted in:

- Estimated Iridium Ground Station Equipment Availability: 0.99997
- Estimated Inmarsat SBB Ground Station Equipment Availability: 0.999999999

Inmarsat SBB can offer very high availability ground systems due to implemented redundancy; without redundancy, Iridium ground system availability performance will not be quite as high.

E.2.1.2.1.2 Satellite Control Equipment

For satellite systems, satellite control equipment failure events are failures associated with network operation centers. Specific components considered for Inmarsat SBB and Iridium FRS components are shown in figure E–98.

In calculating availability for ground control equipment, redundancy, and load sharing was accommodated. This applied to both Iridium and Inmarsat SBB, as both were assumed to provide redundant ground control equipment. As recommended in DO-270, the applied availability formula for this element was the K redundancy with common repair formula, applicable when there are K identical units of which only 1 is needed to maintain service, and failed units are repaired through a common repair facility. Specifically, the formula is as follows: $A_{KC} = 1 - p_K$, where p_K = is the probability that all units are simultaneously under repair, or $p_K = K!(\lambda_{out}/\mu_{out}) * B(K, (\lambda_{out}/\mu_{out}))$ where K is the number of redundant elements; λ_{out} is average failure rate; μ_{out} is the average restoration rate; and $B(K, (\lambda_{out}/\mu_{out}))$ is the "blocked attempts cleared" model or standard Erlang B.

Similar to ground network equipment case, for these architectures, specific outage data was not available from Inmarsat or Iridium. As before, available network control outage information from various sources was used to derive "similar in kind" assumptions applied to both SATCOM architectures. Information gathered on network and satellite control equipment point to trends of highly reliable, redundant implementations. As a result, very little historical failure data was found. This element was not deemed to be a driving factor for service outages, and unrecovered failure examples appear to be traced to geographic power outages. As a result, assumptions addressing the possibility of widespread geographic power outages that may lead to control equipment service interruptions were applied. Specifically, a failure rate of once per 3 years was assumed with outage duration of 24 hours. Applying the formula above (with availability calculated over an observation period of 3 years or 26298 minutes) resulted in:

- Estimated Iridium Ground Control Station Equipment Availability: essentially 1 (as many as twelve 9's)
- Estimated Inmarsat SBB Ground Control Station Equipment Availability: essentially 1 (as many as twelve 9's)

That is, both architectures are estimated to have very high availability performance with regard to ground control equipment.

E.2.1.2.1.3 Aircraft Station Equipment

This component addressed failure events associated with aircraft satellite radio equipment. This would account for installation and local interference effects. Recall as noted above, the focus of the availability analysis was multi-user availability, rather than on connectivity to an individual user. Because aircraft station failures affect individual users, when performing multi-user availability calculations, this element was assumed to have an availability of 1 (consistent with DO-270 approach).

E.2.1.2.1.4 Satellite

The final system component failure element considered was the satellite or spacecraft element. The Inmarsat SBB addressed the single I-4 satellite that would provide SBB service to the NAS. For Iridium, this included all satellites (and crosslinks) in the one or two orbital planes that would provide communication service to NAS coverage areas. Unfortunately, specific failure information on spacecraft failures was not available from Inmarsat or Iridium. Again, more wide-ranging historical satellite failure information was used to estimate general failure trends for this architecture component. In this case, failure anomaly and outage information from the following sources was reviewed:

- "Satellite G&C Anomaly Trends," Brent Robertson & Eric Stoneking, NASA AAS 03-071
- General satellite failure information from http://www.sat-index.com/failures/index.html?http://www.sat-index.com/failures/echo4.html
- NAVY GEOSAT Follow-On (GFO) detailed satellite event log
- "Historical and Recent Solar Activity and Geomagnetic Storms Affecting Spacecraft Operations," Joe H Allen, SCOSTEP, GOMAC 2002
- "Spacecraft Anomalies and Lifetime" by Charles Bloomquist of Planning Research Corporation
- Satellite Insurance Rates on the Rise: Market Correction or Overreaction, Futron Corporation, July 10, 2002
- Informal Iridium tracking site: http://www.rod.sladen.org.uk/iridium.htm

Two categories of spacecraft components were considered for failure analysis, platform components (including electrical power systems, attitude control, mechanical, propulsion, command and data handling, communications, software, and operations) and payload components. Of these components, based on historical failure information, components with the highest failure rates and mean-time-to-repair statistics included the electrical power system (EPS), attitude control system (ACS) and software.

For Inmarsat spacecraft equipment, availability was calculated using historical satellite failure anomaly/outage information and the following relation:

$$A = 1 - \left[\left(\frac{1}{T_{\mathrm{Obs}}} \right) \left(\left\{ \sum_{k} P_{k\ \mathrm{rec}} \left(T_{\mathrm{Out}} \right)_k \right\} + \left\{ P_{\mathrm{Tot}} T_{\mathrm{Out\,Tot}} \right\} \right) \right]$$

Where:

- T_{Obs} = Observation time = assumed mission life = 10 years
- $P_{k\ rec}$ = Probability of recoverable failure for kth equipment element
- $(T_{out})_k$ = Outage time associated with failure and recovery of kth equipment element
- P_{Tot} = Combined probability of total (unrecoverable) equipment failure (0.1%) based on industry bus failure statistics and reasonable assumptions
- $T_{Out\ Tot}$ = Outage due to total failure = time to replace (relaunch/orbit) spacecraft = estimated 3 months

For Iridium, spacecraft availability was calculated based on the assumption that the constellation serving the NAS is composed of one or two orbital planes, each comprising 11 satellites. Calculations were made using the geographical dependent availability formula where a two-region model was used. In one region, the reference area would be serviced by a single orbital plane and the second region would be serviced by two orbital planes (note that it is unclear if this capability is standard in the current Iridium architecture, but, based on satellite coverage capability, it is envisioned that it could be engineered). Additionally for Iridium, as the architecture utilizes satellite crosslinks as part of the service chain, one crosslink was included in the service chain for the area under analysis. It was assumed that a satellite outage affects only the spotbeam associated with the satellite experiencing the outage; that is, any crosslinks it had accommodated before the failure would be routed through neighboring satellites.

The availability observation period for Iridium was set to the median design lifetime, or 6.5 years. The anomaly incident rate, approximately 12%, defined in the referenced NASA study for LEO systems was assumed. For total failure recovery time, the outage time (time to move an in-orbit spare into place) was taken to be 10 days. For orbital plane recoverable failures, two approaches were employed, as follows:

- Approach 1: Use a set of recoverable failures identified in the NASA study (Satellite G&C Anomaly Trends," Brent Robertson & Eric Stoneking, NASA AAS 03-071)
- Approach 2: Assume recoverable satellite failure anomalies are primarily due to weekly scheduled maintenance lasting up to 3 hours (described in the Iridium Implementation Manual, IR-SWG03-WP06, 2-15-06, p. 46) and assumed to affect all satellites in an orbit simultaneously

Applying the approach and formulas above, the following availability calculations were computed:

- Estimated Iridium Satellite Equipment Availability:
  - Approach 1: Average availability/mission life is 0.9995
  - Approach 2: Average availability/mission life is 0.99
- Estimated Inmarsat SBB Satellite Equipment Availability: Average availability/mission life is 0.9999 (over entire airspace)

In regard to the calculation results provided above, it should be noted that availability calculation results are difficult to conceptualize. This is because spacecraft systems tend to be engineered for very high reliability due to inability to perform repairs. As a result, long mean-time-to-repair values are typically the drivers in the availability calculations.

E.2.1.2.2 Fault-Free Rare Events

Fault-free rare events consist of communication outages due to statistically unlikely events not associated with any system failure. The component events are analyzed in the following sections:

- RF Link Event—Section E.2.1.2.2.1
- Capacity Overload Event—Section E.2.1.2.2.2
- Interference Event—Section E.2.1.2.2.3
- Scintillation Event—Section E.2.1.2.2.4

E.2.1.2.2.1 RF Link Event

The RF link event failure model accounts for random RF events (such as severe fading) for which defined system link budgets are not met, which could lead to service outage. As defined in DO-270, RF system link availability can be defined as:

$$A_o = \frac{T_{OBS} - \sum_{k=1}^{N_{OUT}} \left(T_{OUT}\right)_k}{T_{OBS}} = 1 - \frac{N_{OUT}\,\overline{T_{OUT}}}{T_{OBS}}$$

In the formula $\sum(T_{OUT})_k$ is the total interval of time within the observation interval when the RF system link is *not available for use*. Here “available for use” means that the RF link is capable of providing communications <u>with the specified level of integrity</u> while meeting the maximum transfer delay permitted by the operational application. As noted previously, typically the integrity parameter for RF digital links is BER.

Satellite system design allows for outage events that have a very low probability; are not precluded by elements of the system design; and will occasionally occur even when the system is operating within its specifications. In DO-270 appendix B, RF link system performance is based on the parameter, α, which is the probability that the RF link satisfies the link budget by providing the necessary Carrier/Noise (C/N) to meet the BER integrity requirement. Thus, if the performance is observed by sampling the RF link, with each sample defined as an event, then some fraction $1-\alpha$ of all events will not satisfy the link budget.

Typically, α is a design parameter, not an inherent characterization of the satellite link performance. The satellite service provider determines what level of availability it seeks to provide and then selects its hardware operating parameters accordingly to provide enough link margin to mitigate against random link and RF component degradations.

In appendix B of DO-270, the pro forma RF link budgets include margin $M_{C\alpha}$ necessary to meet the specified availability (α) while accommodating typical random losses associated with satellite links including the following:

- Atmospheric Absorption Losses
- Degradation of G/T from the Sun
- Precipitation Loss
- Satellite Antenna Variations
- Satellite Hardware Variations
- LNA Noise Figure Variations
- Polarization Coupling Losses

- Satellite Modulation Imperfections
- Scintillation Loss

Because aeronautical SATCOM links are typically modeled as Rician fading multipath channels, the DO-270 pro forma RF link budgets accommodate fading losses with a Rician fading margin value (included separately from losses itemized above).

As seen from the list above, SATCOM link availability for a specific SATCOM system is highly dependent on numerous system-specific parameter values. For the most part, these parameter values are not readily available from Inmarsat and Iridium. However, some link availability design goals for these two systems have been presented in technical studies. According to the EUROCONTROL AeroBGAN study, a "95% link availability, under worst-case link conditions is the link design criterion" for Inmarsat IV. This value is based on a minimum 5° elevation angle. As yet, Iridium is "silent" on stated availability in the February 2006 draft of the Iridium Technical Manual for ICAO. However, earlier studies state that a link availability of 99.5% at the stated user data rate of 2400 bps, with a packet error rate of 10 to 6 is provided.

Further observations on SATCOM service RF link availability include:

- As a point of comparison, DO-270 specifies multi-year availability of at least 0.993 over an observation time of 1 year
- Inmarsat SBB service has not been in operation long enough for the vendor to gather sufficient RF link availability statistics
- The broad range in operating parameters of SBB (e.g., data rate and transmit power) provides Inmarsat with significant latitude in providing specific levels of RF link availability
  - RF link availability is driven more by business considerations than technical considerations (e.g., the relatively small percentage of Inmarsat business represented by aeronautical services)
- Iridium probably has less latitude in providing a broad range of RF link availabilities
  - Relatively fixed system design based on original Motorola Iridium design and operating parameters (e.g., its limited data rate and data rate range)

Consideration of a wide range of inputs on RF link availability yielded the following :

- Iridium RF Link Availability: 0.995 (as advertised by first-generation operator, observation time is not specified)
- Inmarsat SBB RF Link Availability: 0.95 (design criterion, observation time not specified)

Because it is an operating parameter of a turnkey system, SATCOM system availability is predominately under the control of the service provider and driven by business rather than technical considerations. With no definitive SATCOM service availability specified by the vendors for aeronautical A/G ATC data communications; this parameter is very limited as a useful quantitative criteria for comparison.

E.2.1.2.2.2 Capacity Overload Event

The capacity overload event component accounts for conditions where available communication capacity is overloaded. This study implemented both a simple Erlang B model and a finite source Erlang C model following DO-270 methodology. The focus of the analysis was provision of services in the en route domain, as this is an applicable domain for satellite service and has the highest data rate required per user (in the COCR).

The Erlang B model was used to evaluate the service availability in the case where service requests are processed immediately or dropped immediately. This is also called the Block Calls Cleared model. It assumes no queuing of service requests and provides a more pessimistic estimate of capacity availability.

Another capacity model used for this component analysis was the Erlang C model, also called Blocked Calls Delayed model. Here, requests for service are either served immediately or placed at the end of a first-in, first-out service queue.

Results for analysis of Iridium and Inmarsat SBB capacity performance for a combined ATS and AOC traffic load (defined based on COCR traffic specifications for COCR Phase 2) are provided in Table E–16.

TABLE E–16.—SATCOM CAPACITY ANALYSIS FOR ATS & AOC TRAFFIC

En Route Phase II COCR data for ATS and AOC			
	IRIDIUM (2400 bps user channel)	IRIDIUM (4800 bps user channel)	INMARSAT
Declared and Derived Parameters for Traffic Load Analysis			
Uplink message rate (per aircraft)	0.02648	0.02648	0.02648
Downlink message rate (per aircraft)	0.04023	0.04023	0.04023
Number of aircraft in spotbeam/service volume	923	923	2482
λ_{UP}: Average uplink AMS(R)S service demand rate	24.44104	24.44104	65.72336
λ_{DN}: Average downlink AMS(R)S service demand rate	37.13229	37.13229	99.85086
N_{BLOCK_UP}: Average uplink AMS(R)S block length (at network POA)	29336	29336	29336
N_{BLOCK_DN}: Average downlink AMS(R)S block length (at network POA)	2344	2344	2344
R_D: Nominal user data rate through AMS(R)S (at network POA)	2400	4800	256000
c_{UP}: Number of uplink servers (channels) available for AMS(R)S	80	40	16
c_{DN}: Number of downlink servers (channels) available for AMS(R)S	80	40	16
N_{Q_UP}: Size of queue or buffering supporting AMS(R)S service (Erlang C only)	100	100	100
N_{Q_DN}: Size of queue or buffering supporting AMS(R)S service (Erlang C only)	100	100	100
T_{OD}: Outage definition time (Erlang C only)	5	5	5
$\mu_{UP} = R_D/N_{BLOCKS}$: Average uplink block service rate	0.08181	0.16362	8.72648
$\mu_{DN} = R_D/N_{BLOCKS}$: Average downlink block service rate	1.02389	2.04778	109.21502
$a_{UP} = \lambda_{UP}/\mu_{UP} = \lambda_{UP}{*}N_{BLOCK\_UP}/R_D$: Average uplink traffic intensity	298.7509789	149.3754895	7.531486285
$a_{DN} = \lambda_{DN}/\mu_{DN} = \lambda_{DN}{*}N_{BLOCK\_DN}/R_D$: Average downlink traffic intensity	36.2658699	18.13293495	0.914259437
$\rho_{UP} = a_{UP}/c_{UP} = \lambda/(c\mu) = (\lambda{*}N_{BLOCK})/(cR_D)$: Average traffic intensity per server	3.734387237	3.734387237	0.470717893
$\rho_{DN} = a_{DN}/c_{DN} = \lambda/(c\mu) = (\lambda{*}N_{BLOCK})/(cR_D)$: Average traffic intensity per server	0.453323374	0.453323374	0.057141215
Uplink $K = c_{UP} + N_Q$: Maximum system user population (Erlang C only)	180	140	116
Downlink $K = c_{DN} + N_Q$: Maximum system user population (Erlang C only)	180	140	116
Lower Bound Model from DO-270 (ERLANG B)			
$B(c,a)_{UP}$	0.733427631	0.734608129	0.002750914
$B(c,a)_{DN}$	1.42907E-10	3.56489E-06	4.56493E-15
$A_{CAP\_UP} = 1 - B(c,a)_{UP}$	0.266572369	0.265391871	0.997249086
$A_{CAP\_DN} = 1 - B(c,a)_{DN}$	1	0.999996435	1
Overall availability - Erlang B	0.266572369	0.265390925	0.997249086
ERLANG C (finite source)			
Erlang C Model: Blocked Calls Queued			
(Provides a more realistic estimate of availability)			
Unavailability - UPLINK	Greater Than 1 (no steady state)	Greater Than 1 (no steady state)	1.03764174E-35
Unavailability - DOWNLINK	1.24995E-44	3.11808E-40	4.5228E-139
$A_{CAP\_UL\_ErlangC}$	N/A - No Steady State	N/A - No Steady State	1.00000000
$A_{CAP\_DL\_ErlangC}$	1	1	1
Overall availability - Erlang C (finite source)	N/A	N/A	1

The analysis results shown above indicate that for Iridium, a steady-state condition cannot be achieved for uplink traffic (i.e., the average traffic intensity per server, ρ, is greater than 1). This indicates that there is insufficient capacity in the Iridium system to accommodate the number of users and associated data capacity requirements specified in the COCR for ATS and AOC uplink traffic. For Inmarsat SBB, the Erlang B model results indicate capacity for both uplink and downlink traffic can be met with availability of 0.997. Implementing the more realistic Erlang C model improves availability to approximately 1.

A second calculation of capacity performance was made for ATS only traffic as defined in the COCR (for Phase 2). The results of this analysis are provided in table E–17.

TABLE E–17.—SATCOM CAPACITY ANALYSIS FOR ATS-ONLY TRAFFIC

En Route Phase II COCR data for ATS only			
	IRIDIUM (2400 bps user channel)	**IRIDIUM (4800 bps user channel)**	**INMARSAT**
Declared and Derived Parameters for Traffic Load Analysis			
Uplink message rate (per aircraft)	0.01273	0.01273	0.01273
Downlink message rate (per aircraft)	0.01699	0.01699	0.01699
Number of aircraft in spotbeam/service volume	923	923	2482
λ_{UP}: Average uplink AMS(R)S service demand rate	11.74979	11.74979	31.59586
λ_{DN}: Average downlink AMS(R)S service demand rate	15.68177	15.68177	42.16918
N_{BLOCK_UP}: Average uplink AMS(R)S block length (at network POA)	29336	29336	29336
N_{BLOCK_DN}: Average downlink AMS(R)S block length (at network POA)	2344	2344	2344
R_D: Nominal user data rate through AMS(R)S (at network POA)	2400	4800	256000
c_{UP}: Number of uplink servers (channels) available for AMS(R)S	80	40	16
c_{DN}: Number of downlink servers (channels) available for AMS(R)S	80	40	16
N_{Q_UP}: Size of queue or buffering supporting AMS(R)S service (Erlang C only)	100	100	100
N_{Q_DN}: Size of queue or buffering supporting AMS(R)S service (Erlang C only)	100	100	100
T_{OD}: Outage definition time (Erlang C only)	5	5	5
$\mu_{UP} = R_D/N_{BLOCKS}$: Average uplink block service rate	0.08181	0.16362	8.72648
$\mu_{DN} = R_D/N_{BLOCKS}$: Average downlink block service rate	1.02389	2.04778	109.21502
$a_{UP} = \lambda_{UP}/\mu_{UP} = \lambda_{UP}{*}N_{BLOCK\_UP}/R_D$: Average uplink traffic intensity	143.6215998	71.81079988	3.620688082
$a_{DN} = \lambda_{DN}/\mu_{DN} = \lambda_{DN}{*}N_{BLOCK\_DN}/R_D$: Average downlink traffic intensity	15.31586203	7.657931017	0.386111554
$\rho_{UP} = a_{UP}/c_{UP} = \lambda/(c\mu) = (\lambda{*}N_{BLOCK})/(cR_D)$: Average traffic intensity per server	1.795269997	1.795269997	0.226293005
$\rho_{DN} = a_{DN}/c_{DN} = \lambda/(c\mu) = (\lambda{*}N_{BLOCK})/(cR_D)$: Average traffic intensity per server	0.191448275	0.191448275	0.024131972
Uplink $K = c_{UP} + N_Q$: Maximum system user population (Erlang C only)	180	140	116
Downlink $K = c_{DN} + N_Q$: Maximum system user population (Erlang C only)	180	140	116
Lower Bound Model from DO-270 (ERLANG B)			
$B(c,a)_{UP}$	0.451189893	0.45852573	1.11582E-06
$B(c,a)_{DN}$	2.01834E-31	1.33973E-16	1.06184E-36
$A_{CAP\_UP} = 1 - B(c,a)_{UP}$	0.548810107	0.54147427	0.999998884
$A_{CAP\_DN} = 1 - B(c,a)_{DN}$	1	1	1
Overall availability - Erlang B	0.548810107	0.54147427	0.999998884
ERLANG C (finite source)			
Erlang C Model: Blocked Calls Queued			
(Provides a more realistic estimate of availability)			
Unavailability - UPLINK	Greater Than 1 (no steady state)	Greater Than 1 (no steady state)	6.54239E-71
Unavailability - DOWNLINK	6.474E-103	4.29726E-88	2.8801E-182
$A_{CAP\_UL\_ErlangC}$	N/A - No Steady State	N/A - No Steady State	1
$A_{CAP\_DL\_ErlangC}$	1	1	1
Overall availability - Erlang C (finite source)	N/A	N/A	1

Again, for Iridium, a steady-state condition cannot be achieved for uplink traffic. This indicates that Iridium capacity cannot accommodate the full set of air traffic users (as defined in the COCR for the en route environment) with the associated ATS message set.

Summarizing the results of the analysis above:

- Iridium Capacity Availability: Availability of downlink traffic capacity is approximately 1 for both ATS-only and ATS and AOC traffic loads; no steady state can be achieved for uplink traffic

- Inmarsat SBB Capacity Availability: Availability of uplink and downlink traffic capacity is approximately 1 for both ATS-only and ATS and AOC traffic loads

The values above represent results of calculations that employ the Erlang C model, with an assumed queue size of 100 and declared outage after queuing for 5 seconds.

E.2.1.2.2.3 Interference Event

The interference event component accounts for the aggregated interference environmental effects from external sources that may lead to service outage. For satellite systems, this accounts for emissions from other SATCOM AMS(R)S communication systems operating from other aircraft in the same operating space.

DO-270 establishes the requirement that a SATCOM system shall provide adequate performance in the presence of aggregated interference from external sources equivalent to 25% of the total noise power in the received RF channel. There are occasionally instances where substantially higher levels of interference are experienced, which exceed the system design requirement and thus cause service outages. A volumetric availability model based on DO-270 was used to calculate the unavailability due to potential excessive interference between SATCOM-equipped aircraft operating in the same airspace. The defined model for this study is shown in figure E–99.

The volumetric model shown determined the probability that "victim" aircraft using a different SATCOM system would be within an "interference volume" of the transmitting source aircraft. Interference availability was computed as follows:

$$A = 1 - \left[L_E * P_V * \left(\sum_k V_K \right) \right]$$

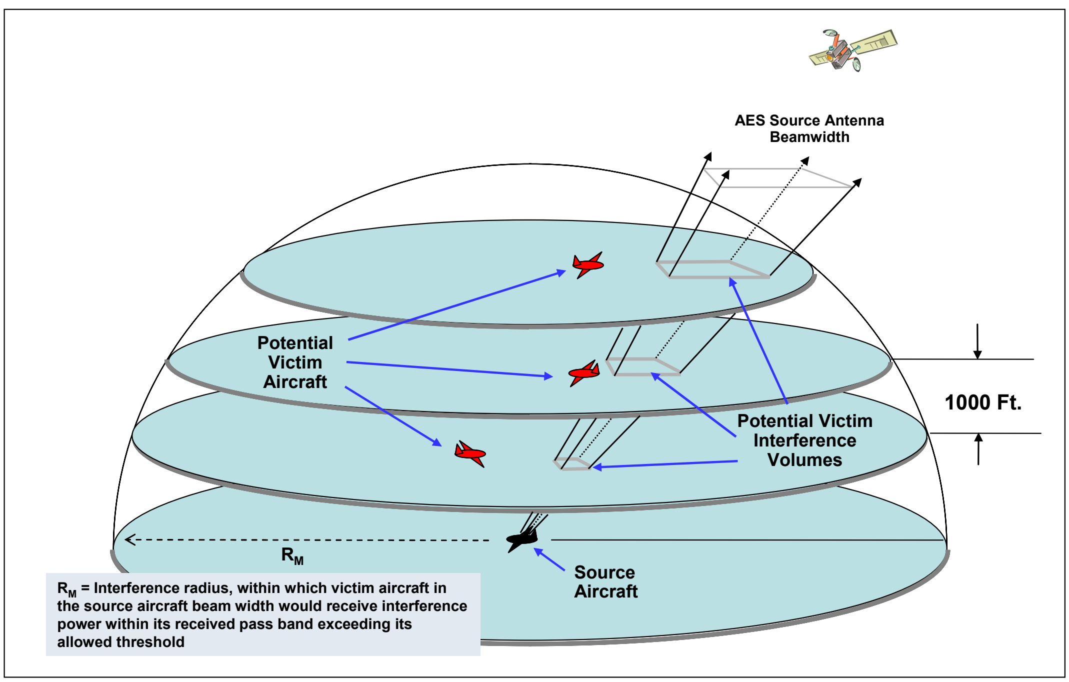


Figure E–99.—Volumetric Model for Interference Event Analysis.

Where:

- L_E = Average traffic load of source aircraft, based on traffic loading models developed for capacity overload availability calculations
- P_V = Probability a victim aircraft is in an interference volume, based on a COCR uniform density assumption for Phase 2 en route airspace
- V_K = Interference volume at flight level k

A representation of the possible multiple interference volumes at each of the flight levels of interest (e.g., flight level k) is shown in figure E–100.

Within the airspace of interest used for the analysis, it was assumed that 50% of the aircraft were Inmarsat SBB equipped and 50% of the aircraft were Iridium equipped. Applying the availability formula above to the defined interference volume model, the following results were calculated:

- Iridium Interference Event Availability: 0.996 for en route airspace
- Inmarsat SBB Interference Availability: Approximately 1 for en route airspace

Within this analysis, it was concluded that Iridium interference availability may be an issue because of the robust Inmarsat I-4 SBB AES power levels and high gain antennas necessary to provide the high SBB data rates to the GEO spacecraft. The value calculated can be considered bound to the availability as it was assumed that Inmarsat source aircraft used all 16 available communication channels within a single spot beam and all 16 aircraft simultaneously transmitting.

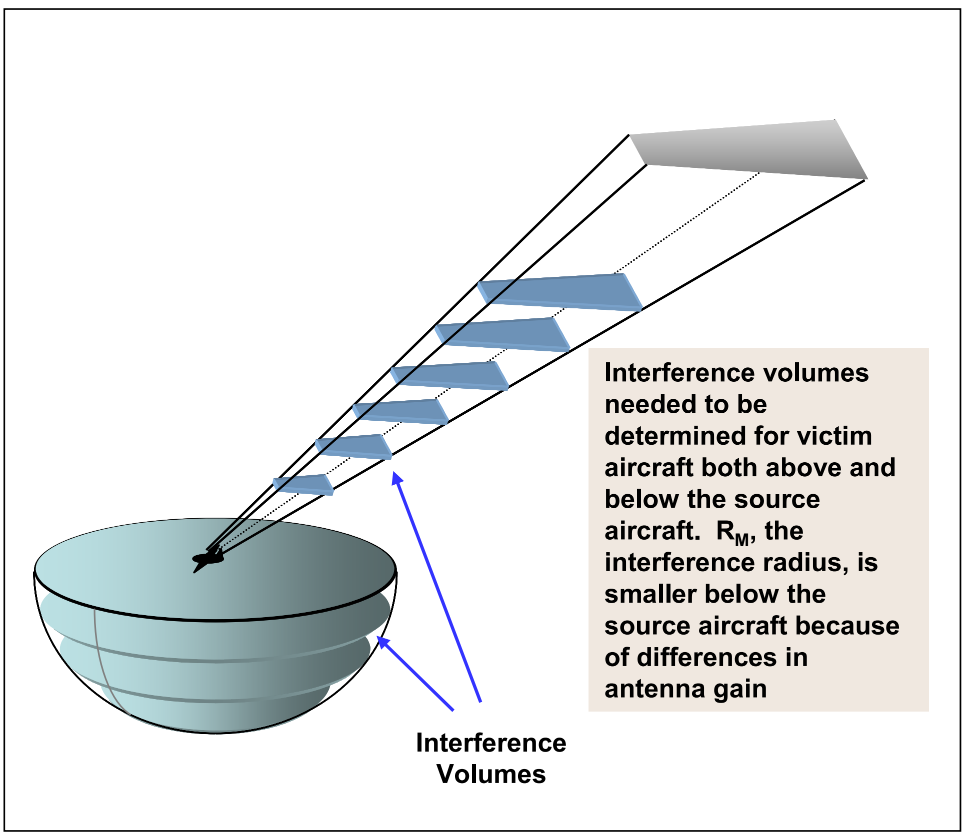


Figure E–100.—Interference Volumes of Interest.

E.2.1.2.2.4 Scintillation Event

The final fault-free component considered was scintillation. This element accounts for ionospheric events involving the Sun and the Earth's magnetic field, which produce random variations in electromagnetic waves traversing the ionosphere. Upon investigation of scintillation effects (reference *Propagation Effects Handbook for Satellite System Design*, Ippolito 2000), significant impact on satellite communications occurs in the equatorial latitudes (+/–20° latitude) and in the polar regions (above 65° latitude). As such, for the middle latitudes that constitute the region of interest for the NAS, there are minimal scintillation effects. Availability of approximately 1 was assumed for this component for both SATCOM architectures.

E.2.1.3 VHF Terrestrial Availability Calculations

As a point of comparison, the satellite availability calculations were considered in contrast to similar calculations made for a VHF terrestrial architecture. The selected representative VHF data architecture was considered to be a regular grid of ground stations implementing a VHF technology (such as VDL Mode 2).

E.2.1.3.1 Analyzed Architecture

Similar to the definitions developed for the SATCOM architectures, a block diagram identifying FRS components of the VHF terrestrial architecture was created. This block diagram is provided in figure E–101.

The architecture defined above includes primary/backup radio redundancy where component redundancy within each primary or backup radio site is assumed to be similar to current Remote Communication Air/Ground (RCAG) and Back Up Emergency Communications (BUEC) configurations, respectively.

E.2.1.3.2 Availability Calculations

A fault tree failure analysis model, similar to what was defined for the satellite availability calculations, was also used for VHF terrestrial architecture availability analysis. However, not all of the components defined for satellite architecture analysis apply. Specifically, a network operation center does not explicitly affect availability of terrestrial communications (e.g., there is no telemetry, tracking, and control operations), thus there is no network control component; thus, there also is no spacecraft component. For fault-free failures, scintillation is not an applicable factor for VHF communications and was not included in the terrestrial analysis. The remaining factors are addressed below for the terrestrial communication architecture.

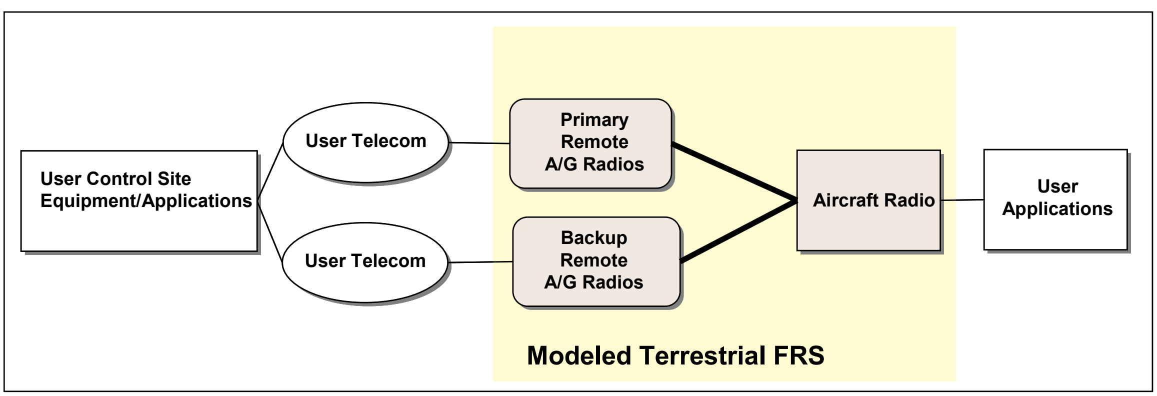


Figure E–101.—VHF Terrestrial Modeled Architecture.

E.2.1.3.2.1 System Failure Components

Two factors were considered in this category. The first, aircraft station equipment was assigned an availability value of 1 (similar to the SATCOM analysis) as the focus of this study is on multi-user outages. Reference section E.2.1.2.1.3 above for additional information. The second system component considered for availability analysis was the ground station equipment. Identification of the model elements specific to this component is shown in figure E–102.

A more detailed view of individual elements that comprise the primary and backup radio equipment sites (based on current RCAG/BUEC sites, as described earlier) is provided in figure E–103.

To calculate individual radio site element availabilities, mean-time-between-failure (MTBF) and MTTR values for terrestrial equipment, as specified in the NEXCOM System Requirements Document (SRD) appendix E, were applied. These were considered to be within reasonable range of requirements to be specified for any new VHF terrestrial data network. The resulting estimated availability is as follows:

- VHF Terrestrial Ground Station Availability: 0.99999 (for yearly observation for all coverage area)

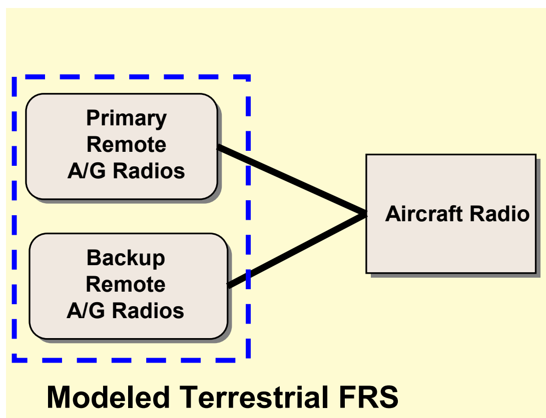


Figure E–102.—Modeled Ground Station Components.

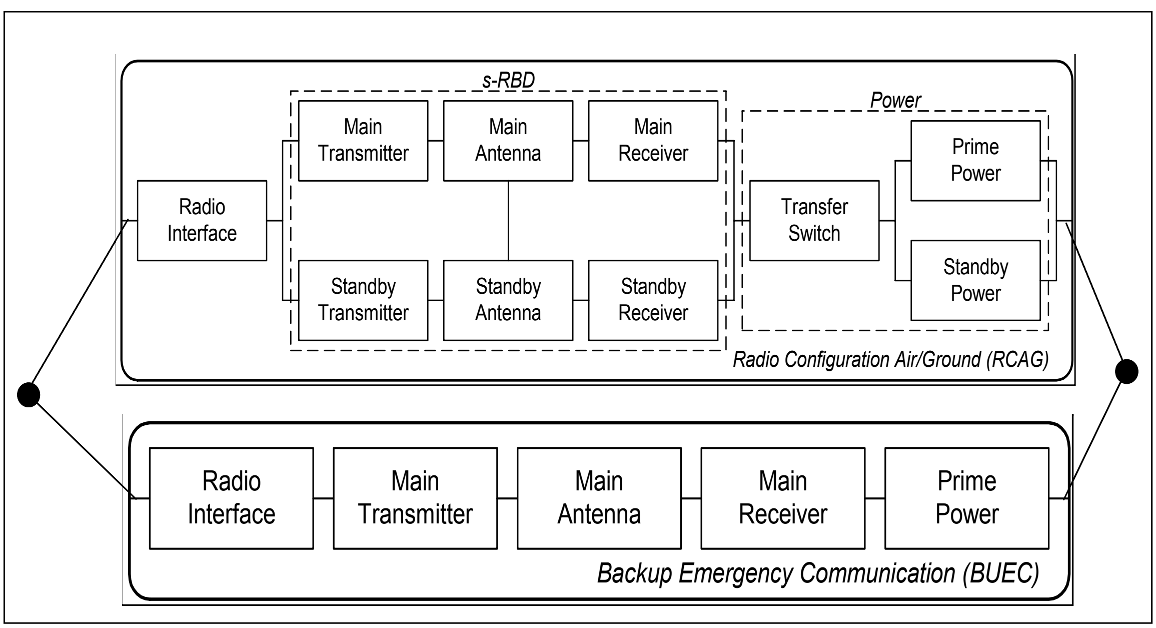


Figure E–103.—Expanded View of Terrestrial Radio Site Equipment.

E.2.1.3.2.2 Fault-Free Rare Events

Three types of fault-free events were considered for the VHF terrestrial architecture. These included RF Link Events; Capacity Overloads; and Interference Events.

As indicated above, the RF link event is more closely tied to design parameters than to inherent system performance. As such, design requirements for VHF terrestrial networks were explored. The RTCA document outlining performance requirements for aeronautical air/ground systems (DO-224B) notes that "the service availability goal of the end-to-end communication system" for data service is 0.999 (section 2.4.1). For this value, the observation time is not specified. This value is utilized for this component contributor for the VHF terrestrial architecture.

Similar to the SATCOM capacity analysis, the Erlang B and Erlang C models were used to examine terrestrial architecture capacity performance with regard to COCR-specified traffic loads. Table E–18 documents VHF terrestrial architecture performance for a combined ATS and AOC traffic load (COCR Phase 2 requirements).

TABLE E–18.—VHF TERRESTRIAL CAPACITY ANALYSIS FOR ATS AND AOC TRAFFIC

En Route Phase II COCR data for ATS and AOC	Terrestrial VHF - low data rate	High Data Rate Terrestrial
Declared and Derived Parameters for Traffic Load Analysis		
Message rate (per aircraft)	0.06671	0.06671
Number of aircraft in spotbeam/service volume	95	95
λ: Average AMS(R)S service demand rate	6.33745	6.33745
N_{BLOCK}: Average AMS(R)S block length (at network POA)	13056	13056
R_D: Nominal user data rate through AMS(R)S (at network POA)	10000	288000
c: Number of servers (channels) available for AMS(R)S	1	1
N_Q: Size of queue or buffering supporting AMS(R)S service (only for Erlang C)	100	100
T_{OD}: Outage definition time (only for Erlang C)	5	5
$\mu = R_D/N_{BLOCKS}$: Average block service rate	0.76593	22.05882
$a = \lambda/\mu = \lambda * N_{BLOCK}/R_D$: Average uplink traffic intensity	8.27417472	0.287297733
$\rho = a/c = \lambda/(c\mu) = (\lambda * N_{BLOCK})/(cR_D)$: Average traffic intensity per server	8.27417472	0.287297733
$K = c + N_Q$: Maximum system user population (only for Erlang C)	9	9
Lower Bound Model from DO-270 (ERLANG B)		
Erlang B Model: Request for service is served immediately or dropped immediately		
(Provides a pessimistic or lower bound estimate of availability)		
$B(c,a) = (a^c/c!) / (SUM[n=0,c](a^n/n!))$		
B(c,a)	0.892173694	0.223178932
A_{CAP_UP} = 1 - B(c,a)	0.107826306	0.776821068
ERLANG C (finite source model)		
Unavailability	Greater Than 1 (no steady state)	2.08835E-35
$A_{CAP\_ErlangC}$	N/A - No Steady State	1

A low data rate VHF terrestrial architecture does not provide sufficient capacity to provide a steady-state system or reasonable availability for the combined ATS & AOC traffic load

A higher data rate reference terrestrial architecture (e.g. value based on the reference architecture developed for L-band business case) provides sufficient capacity with availability of approximately 1 for the combined ATS & AOC traffic load when considering the Erlang C model

As shown in table E–18, two types of terrestrial networks were examined. The first, in the middle column, is the representative VHF terrestrial data communication network analysis. For this architecture, similar to the Iridium capacity analysis results, a steady-state condition could not be achieved. In other words, the VHF reference architecture (with data rates based on VDL Mode 2 performance) provides insufficient capacity to accommodate a combined ATS and AOC traffic load (per COCR Phase 2 requirements). As a second point of reference for terrestrial architectures, a second analysis, representative of a high-data-rate architecture such as those proposed for L-Band implementation, was examined. This second architecture provides capacity availability performance of approximately 1 (for Erlang C model).

The ATS-only traffic load was also investigated for the representative terrestrial architecture. Results of this analysis are provided in table E–19.

TABLE E–19.—VHF TERRESTRIAL CAPACITY ANALYSIS FOR ATS-ONLY TRAFFIC

En Route Phase II COCR data for ATS only		
	Terrestrial VHF - low data rate	**High Data Rate Terrestrial**
Declared and Derived Parameters for Traffic Load Analysis		
Message rate (per aircraft)	0.02972	0.02972
Number of aircraft in spotbeam/service volume	95	95
λ: Average AMS(R)S service demand rate	2.8234	2.8234
N_{BLOCK}: Average AMS(R)S block length (at network POA)	13056	13056
R_D: Nominal user data rate through AMS(R)S (at network POA)	10000	288000
c: Number of servers (channels) available for AMS(R)S	1	1
N_Q: Size of queue or buffering supporting AMS(R)S service (only for Erlang C)	100	100
T_{OD}: Outage definition time (only for Erlang C)	5	5
$\mu = R_D/N_{BLOCKS}$: Average block service rate	0.76593	22.05882
$a = \lambda/\mu = \lambda * N_{BLOCK}/R_D$: Average uplink traffic intensity	3.68623104	0.127994133
$\rho = a/c = \lambda/(c\mu) = (\lambda * N_{BLOCK})/(cR_D)$: Average traffic intensity per server	3.68623104	0.127994133
$K = c + N_Q$: Maximum system user population (only for Erlang C)	9	9
Lower Bound Model from DO-270 (ERLANG B)		
Erlang B Model: Request for service is served immediately or dropped immediately		
(Provides a pessimistic or lower bound estimate of availability)		
$B(c,a) = (a^c/c!) / (SUM[n=0,c](a^n/n!))$		
B(c,a)	0.786608899	0.113470567
A_{CAP_UP} = 1 - B(c,a)	0.213391101	0.886529433
ERLANG C (finite source model)		
Unavailability	Greater Than 1 (no steady state)	2.1777E-43
$A_{CAP\_ErlangC}$	N/A - No Steady State	1

As with the ATS&AOC combined traffic results, the low data rate VHF terrestrial architecture does not provide sufficient capacity to provide a steady-state system; the higher data rate reference terrestrial architecture, however, does provide sufficient capacity with high availability (approx. 1)

Similar results were calculated for the ATS-only traffic load, where it was found that the VHF terrestrial architecture (based on VDL Mode 2 data capacity performance) cannot provide a steady-state solution, while the high-data-rate terrestrial architecture could provide capacity with availability of approximately 1 (for Erlang C model).

The final fault-free component considered for the terrestrial architecture was the interference event. Here there was no directly analogous case with which to compare with the SATCOM cases, that is, two SATCOM systems operating in the same airspace, but with adjacent frequency allocations. Therefore, the potential interference availability for a slightly analogous case of aircraft in the same airspace, but using different VHF frequencies/channels (e.g., ATC and AOC channels) was calculated. Using DO-186A (VHF radio MOPS) parameters and a volumetric model similar to that for the SATCOM systems, it was determined that the interference radius RM was so low (well below the 1000-foot minimum vertical spacing separation standard for aircraft) as to result in no interference volumes, thus making availability essentially one.

E.2.1.4 Summary

A summary of all availability results is provided in table E–20. As shown, the limiting factors for SATCOM systems are satellite equipment failures and RF link events; capacity overload (Iridium) and interference (Iridium). For the VHF terrestrial communication system, the limiting factors are capacity overload and RF link events.

TABLE E–20.—SUMMARY OF AVAILABILITY ANALYSIS RESULTS

	System Component Failures				Fault-Free Rare Events			
	Ground Station	Control Station	Aircraft Station	Satellite	RF Link	Capacity Overload	Interference	Scintillation
Inmarsat	~ 1	~ 1	~ 1	0.9999	0.95	~ 1	~ 1	~ 1
Iridium	0.99997	~ 1	~ 1	0.99	0.995	- [1]	0.996	~ 1
VHF Terrestrial	0.99999	N/A	~ 1	N/A	0.999	- [2]	~ 1	N/A

Notes:

1. Iridium Capacity Overload availability of AES to SATCOM traffic is essentially one (1) (for both ATS only and ATS & AOC). No steady-state can be achieved for SATCOM to AES traffic.
2. Terrestrial Capacity Overload availability is for VHF-Band reference architecture business case; for L-Band Terrestrial Capacity Overload availability would be essentially one (1).

Caution is needed for interpretation of the provided availability results. Because certain SATCOM availability data is unavailable, many of the availability contributors have been estimated by “similar in kind” systems and will be influenced by specific system implementation and/or margins incorporated to improve performance. Additionally, the focus has been on availability alone, but other criteria to assure suitability of a communication channel must also be investigated. This includes, for example, long-and short-term reliability (i.e., continuity of service) and restoration time.

E.2.2 Cocr Service Provisioning Using Satellite Communications

The COCR specifies performance requirements for data capacity; latency; QoS; number of users; security; and availability. As noted previously, availability was not explicitly evaluated as part of the general technology assessment (AHP step 6). This is due to the characterization of availability as a design factor, and, for most evaluated technologies, as specific architecture is not defined. However, for a subset of the satellite architectures, the architectures were defined and therefore availability could be explicitly considered. This is important as the SATCOM availability metric is a potential driver for determining the applicability of SATCOM technologies to COCR service provisioning.

COCR version 1.0 specifies availability for the FRS based on availability parameters and associated definitions provided in RTCA DO-290. In this document, two parameters are defined, including:

- Availability of Use (A_U)—the probability that the communication system between two parties is in service when needed
- Availability of Provision (A_P)—he probability that communication with all aircraft in an area is in service

A_U addresses connectivity to a user and includes the performance of user installations that are part of the communication link. This parameter is appropriate for specifying single user availability that accounts for specific aircraft station availability. A_P is a requirement on the air traffic service provider. It is appropriate for multi-user availability calculations that focus on service provision to an entire service volume (and does not account for individual aircraft station availability contributions). As the focus of the detailed SATCOM analysis was on multi-user availability, consideration of COCR service provisioning over SATCOM systems used the A_P requirements of the COCR.

As a point of reference, COCR service availability requirement examples are shown in tables E–21 and E–22.

TABLE E–21.—COCR PHASE 1 AVAILABILITY REQUIREMENT EXAMPLES

Service	Latency (RCTP - 1 way)					Integrity	Availability	
	APT	TMA	ENR	ORP	AOA			
	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$
ACL	3.8	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965
ACM	3.8	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965
ADS-B	0.80	4.8	9.6	9.6	-	5.0E-6	0.9995	0.9965
A-EXEC	-	-	-	-	-	-	-	-
AIRSEP	-	-	-	-	-	-	-	-
AMC	3.8	3.8	3.8	26.5	-	5.0E-4	0.9995	0.9965
ARMAND	-	-	9.2	-	-	5.0E-6	0.9995	0.9965
C&P	-	3.8	3.8	26.5	-	5.0E-6	0.9995	0.9965

TABLE E–22.—COCR PHASE 2 AVAILABILITY REQUIREMENT EXAMPLES

Service	Latency (RCTP - 1 way)					Integrity	Availability	
	APT	TMA	ENR	ORP	AOA			
	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$TD_{95\text{-}FRS}$	$I_{UCT\text{-}FRS}$	$A_{P\text{-}FRS}$	$A_{U\text{-}FRS}$
ACL	1.4	1.4	1.4	1.4	1.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
ACM	1.4	1.4	1.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
ADS-B	0.8	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
A-EXEC	-	0.74	0.74	0.74	-	5.0E-10	1-(5.0E-10)	1-(5.0E-8)
AIRSEP	-	-	-	-	8.0	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
AMC	1.4	1.4	1.4	1.4	1.4	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
ARMAND	-	-	4.7	-	-	5.0E-5	1-(5.0E-5)	1-(5.0E-4)
C&P	-	2.4	2.4	2.4	-	5.0E-8	1-(5.0E-8)	1-(5.0E-6)
COTRAC	-	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-6)	1-(5.0E-5)
D-ALERT	2.4	2.4	2.4	2.4	2.4	5.0E-8	1-(5.0E-8)	1-(5.0E-6)

For ATS service, COCR Phase 1 A_P requirements are all equal to 0.9995. For COCR Phase 2, two groupings of availability requirements are considered. The first group includes all CCOR services, including a service called “Automatic Execution Service” or A-EXEC with very high associated availability requirements. The second group includes all COCR services except A-EXEC. The A-EXEC service is specified to provide an automated safety net to capture situations where wake turbulence separation is being used and a nonconformance event occurs with minimal time remaining to resolve the conflict. Due to this defined role in the NAS, this service has extremely stringent availability requirements. COCR Phase 2 ATS requirements are summarized as follows:

- With A-EXEC: availability ranges from 0.9995 to 0.9999999995 (also denoted $(.9)_9 5$)
- Without A-EXEC: availability ranges from 0.9995 to 0.99999995 (also denoted $(.9)_7 5$)

For AOC services, COCR Phases I and II AP requirements range from 0.9995 to 0.999995 (also denoted $(.9)_5 5$).

The requirements above have been compared with availability analysis results summarized in table E–22. Several conclusions can be drawn:

- Inmarsat SBB and perhaps Iridium may provide sufficient availability performance to meet a subset of COCR service availability performance requirements in limited applications
- It is clear, however, that these SATCOM architectures will not provide sufficient availability to provision most if not all of the COCR services defined for Phase 2 operations

These results are in line with other recent studies that have investigated Inmarsat and Iridium availability performance. A recent EUROCONTROL study, Inmarsat SBB Services for Air Traffic Control, does not include explicit calculations of availability, but indicates that the offered services are not sufficient for providing a stand-alone solution for future ATS. Additionally, a Boeing GCNSS-COCR Phase 1 study included availability analysis supporting a proposed SATCOM architecture, the NAS ATS. Although individual calculation details are not available, the study indicated that in part to meet availability requirements, the recommended architecture would necessitate a five-satellite infrastructure.

Although it is concluded that Inmarsat SBB (and Iridium) are not likely viable stand-alone solutions for the FRS, this by no means indicates that these SATCOM systems would not have a meaningful role in specific domains (e.g., oceanic/remote) and/or specific limited applications (e.g., disaster recovery).

Additionally, these results do not preclude consideration of other SATCOM systems to provide a wider role in provisioning ATS services. Proposed custom architectures, for example, SDLS may be specifically designed for ATS and architected to meet all COCR requirements.

E.2.3 Hybrid Satellite Communication Architectures

As evaluated, SATCOM architectures were found to not be viable stand-alone solutions for the FRS. Thus, brief consideration was given to the role of satellites as part of future hybrid architecture solutions for the FRS. It should be noted that the current aeronautical infrastructure can be considered a hybrid architecture of this nature. Continental communications are provisioned by terrestrial architectures and oceanic/remote communications are provided by satellite and/or HF data link architectures. Additionally, there has been limited use of SATCOM for providing temporary recovery of ground communications (e.g., after hurricane Katrina in 2005) and for providing circuit backup (e.g., FAASAT). Although many hybrid architecture possibilities exist, a few were selected for qualitative evaluation and comparison in this study. A list of six candidate architecture alternatives, and identification of three selected for analysis in this study (indicated by shading), are shown in table E–23.

TABLE E–23.—SELECTED SATCOM HYBRID ARCHITECTURES

Architecture Name	Description	Rationale for Further Consideration
1. Dual GEO/LEO Satellite Architecture	GEO satellite architecture backup to LEO architecture or vice versa	**Evaluated Further – specifically identified in SOW**
2. Terrestrial with Satellite Backup	Terrestrial network that has “stand-by” access to a backup satellite network	Not Considered: Disaster Recovery use of satellite may be addressed by increasing the geographic-based coverage (from scenario 5 below); cost-prohibitive as a standalone solution
3. Satellite with Terrestrial Backup	Satellite service that has “stand-by” access to backup terrestrial network	Not Considered: Cost prohibitive to implement terrestrial “backup” network or to maintain capacity reserve in an existing terrestrial system to address a full satellite load
4. Shared services across joint terrestrial/satellite architecture	Full complement of service available to users from both terrestrial and satellite architecture components – fully redundant architecture	Not Considered: Requires maintaining two fully redundant systems to be used on demand; cost prohibitive, complex and no sizeable benefit over architecture 6 (static allocation of services to systems)
5. Geographic-based allocation of services across terrestrial/ satellite architecture	Terrestrial services are used in some areas of the service volume while satellite services are used in other areas of the service volume	**Evaluated Further – current operational Implementation**
6. Service-based allocation of services across terrestrial/ satellite architecture	Some services are provisioned over terrestrial services while others are provisioned over satellite services	**Evaluated Further**

As an introduction, a summary of key considered architecture information for evaluated hybrid architectures in provided in figures E–104, E–105, and E–106.

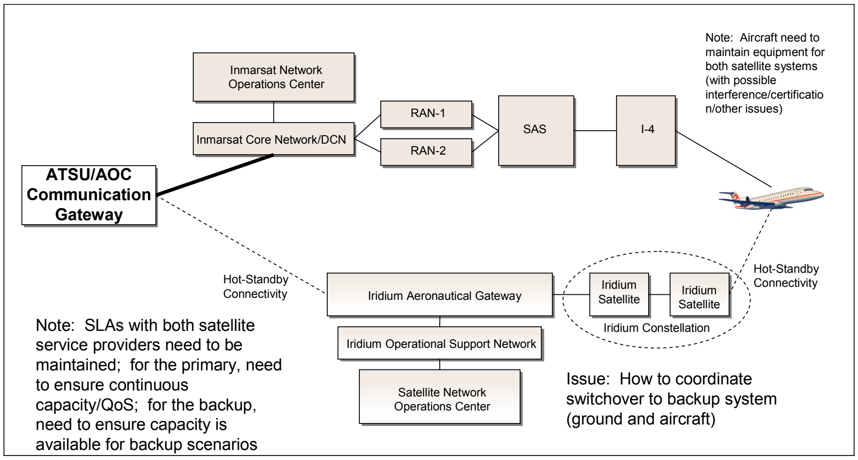


Figure E–104.—Dual GEO/LEO SATCOM Hybrid Architecture.

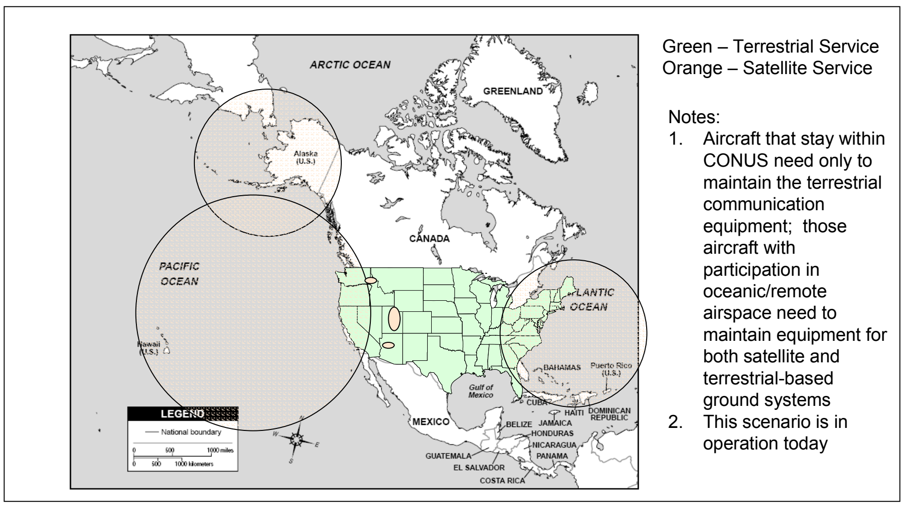


Figure E–105.—Geographically-Based Terrestrial-Satellite Hybrid Architecture.

- <u>COCR Services over Terrestrial Communication Services</u>
  - ATS Services
    - Controller/Flight Crew Services (e.g. ACL, AMC, D-TAXI, DCL, DSC, PPD, DYNAV)
    - Traffic & Surveillance
    - Emergency and Ancillary (URCO and D-ALERT)
    - Communication Management (DLL and ACM)
    - Auto-Downlink and FIS in Airport Domain
  - AOC Services
    - Services allocated in some flight domain to service class J (most stringent AOC service class)
      - Includes Login, OOOI, Flight Status, Gate Info, Maintenance, Flight Plan, Loadsheet, Graphical Weather and Real-Time Weather
- <u>COCR Services over Satellite Communication Services</u>
  - ATS Services (when not in airport domain)
    - Automated Downlink of Airborne Parameters
      - Includes FLIPCY, FLIPINT and SAP
    - Flight Information Services
      - Includes D-OTIS, D-RVR, D-ORIS, D-SIGMET, D-ATIS, D-FLUP, D-SIG
  - AOC Services
    - Services not included in service class J and not in the airport domain
      - Includes NOTAMs, Free Text, Position Report, Fuel Status, Engine Performance, Flight Log, Real-Time Maintenance, etc.

Notes: 1) SLAs with satellite service provider need to be maintained; and connectivity provided between appropriate ground systems and satellite ground interface; 2) Aircraft need to equip with both terrestrial-based and satellite-based communication systems (when ATS services are mandated)

Issue: Coordinate switchover of received data from terrestrial to satellite system when leaving airport domain (for services that are existing in airport domain but serviced by SATCOM system outside the airport domain)

Figure E–106.—Service-Based Terrestrial/Satellite Hybrid Architecture.

A qualitative analysis of candidate hybrid architectures was made based on the following criteria:

- Meets COCR service functional requirements
  - Considers ability to provide required service connectivity (e.g., A-G, A-A, etc.), service domains (e.g., en route, O/R/P, etc.), addressed versus broadcast, etc.
- Meets COCR service performance requirements
  - General considerations for availability, latency, QoS, and security
- Relative Ground Infrastructure/Airborne Installation Cost
- Relative Technical Risk
- Relative Benefits

The analysis results specific to each of the criteria noted above are shown in tables E–24, E–25, E–26, E–27, and E–28, respectively.

TABLE E–24.—EVALUATION OF HYBRID ARCHITECTURES—FUNCTIONAL REQUIREMENTS

	Function/Service				Notes
	ATS A/G & G/A Addressed	ATS Ground Broadcast	ATS A/A Addressed	AOC A/G & G/A Addressed	
A. Dual GEO/LEO Satellite Architecture	√	√	√	√	This architecture is capable of addressing the functional communication requirements of the COCR for ATS and AOC services
B. Geographic-Based Allocation of Services	√	√	√	√	This architecture is capable of addressing the functional communication requirements of the COCR for ATS and AOC services
C. Service-Based Allocation Across Terrestrial/ Satellite Architecture	√	√	√	√	This architecture is capable of addressing the functional communication requirements of the COCR for ATS and AOC services;

TABLE E–25.—EVALUATION OF HYBRID ARCHITECTURES—PERFORMANCE REQUIREMENTS

	Performance					Additional Notes
	Number of Users	Data Rate		QOS	Availability	
		ATS - only	ATS & AOC			
A. Dual GEO/LEO Satellite Architecture	√	√	√	Unclear	Partial	With parallel operation of the SATCOM systems, assuming availability on the order of .999 for each system, the total availability is on the order of .999999, which provides similar capabilities to terrestrial architectures, and can meet all Phase I COCR availability requirements and some requirements for Phase II (e.g. FIS services, but not A/A service requirements)
B. Geographic-Based Allocation of Services	√	√	√	Partial	Partial	The SATCOM architecture offerings (as estimated in this study) do not alone meet the stated service provisioning requirements of the COCR (Phase I and II); thus the geographic areas allocated to satellite may not meet all performance requirements. For those regions allocated terrestrial systems, it is anticipated that appropriate design of the system can led to meeting all Phase I and II COCR requirements. It should be noted that one Phase II service (A-EXEC) has a very high availability requirement that in and of itself could drive architecture design and cost. With this service, the terrestrial architecture required to meet performance would likely be prohibitively expensive; without it, an architecture with redundancies more similar to today's terrestrial aeronautical systems could be utilized to satisfy COCR requirements.
C. Service-Based Allocation Across Terrestrial/ Satellite Architecture	√	√	√	Partial	Partial	For the selected representative architecture, the capacity, data rate and number of users parameters can likely be addressed during architecture design. The QoS provisions for SATCOM aeronautical offerings are not fully described and it is unclear if required QoS provisioning will be met. The SATCOM architecture offerings (as estimated in this study) do not alone meet the state service provisioning requirements of the COCR (Phase I and II); thus the services allocated to satellite may not meet all performance requirements. For those services allocated terrestrial systems, it is anticipated that appropriate design of the system can led to meeting all Phase I and II COCR requirements. It should be noted that one Phase II service (A-EXEC) has a very high availability requirement that in and of itself could drive architecture design and cost. With this service, the terrestrial architecture required to meet performance would likely be prohibitively expensive; without it, an architecture with redundancies more similar to today's terrestrial aeronautical systems could be utilized to satisfy COCR requirements.

TABLE E–26.—EVALUATION OF HYBRID ARCHITECTURES—RELATIVE COST

Architecture Name	Applicable Factors	Relative Cost Estimate	Additional Notes
A. Dual GEO/LEO Satellite Architecture	• Ground infrastructure: connectivity to two satellite gateways; • Aircraft installation: includes two satellite transponders (one for each system)	***High***	On the ground, connectivity with two SATCOM service providers and SLAs for sufficient communication capacity requires a high relative cost as compared to a non-hybrid system; aircraft installation requires a high relative cost as compared to a non-hybrid system as multiple SATCOM equipment is required. This solution may have a similar relative cost to architecture C, but perhaps greater than architecture B, which does not require all aircraft to have dual system equipage.
B. Geographic-based allocation of services across terrestrial/ satellite architecture	• Ground infrastructure: connectivity to terrestrial communication systems for CONUS and satellite gateways (from control facilities that are responsible for geographic areas allocated to SATCOM) • Aircraft Installation: Those aircraft that fly in regions allocated to SATCOM, include both SATCOM and Terrestrial COM transceivers; aircraft that do not participate in geographic regions allocated SATCOM do not require SATCOM transceiver equipage	***Moderate***	On the ground, connectivity is typically with one communication system; for facilities responsible for CONUS operations, the communication system is terrestrial, while for oceanic, it is a SATCOM system. Moderate cost is required to implement new systems and connectivity. For aircraft equipage, again the cost is moderate. Its relative cost is greater that non-hybrid configurations; however only aircraft participating in geographic areas designated for SATCOM require dual system equipage. This solution is likely to have a lower relative cost as compared to architectures A and C.
C. Service-based allocation of services across terrestrial/ satellite architecture	• Ground infrastructure: requires connectivity to both terrestrial and satellite ground infrastructure • Aircraft installation: all aircraft require both terrestrial-based and SATCOM-based communication transceivers	***High***	On the ground, connectivity with both a terrestrial and SATCOM service provider/system requires a high relative cost as compared to a non-hybrid system; however, it may support longer life for initially deployed low data rate data communication systems. Aircraft installation requires a high relative cost as compared to a non-hybrid system as both terrestrial-based and SATCOM based transceivers are required. This solution may have a similar relative cost to architecture A, but perhaps greater that architecture B, which does not require all aircraft to have dual system equipage.

TABLE E–27.—EVALUATION OF HYBRID ARCHITECTURES—TECHNICAL RISK

	Factor				Overall Assessment
	Transition	Switchover to Backup	Ground Infrastructure	Airborne Implementation	
A. Dual GEO/LEO Satellite Architecture	This architecture represents a new concept for NAS ATC; transition would likely be complex (high risk)	Switchover between primary SATCOM and backup SATCOM would be complex both for ground and aircraft installations (high risk)	Need to design and implement interfaces to multiple SATCOM GES, NOCCs etc. but could be engineered (modest risk)	Need aircraft architecture that can operate and accommodate ATS and AOC traffic across a primary/backup architecture with two distinct SATCOM systems (moderate risk)	***High Risk***
B. Geographic-Based Allocation of Services	Variants of this architecture are in use today. Transition could likely be engineered with low risk	Not applicable	Need to design and implement new interfaces to SATCOM and terrestrial systems (modest risk)	Similar to architectures in use today (low risk)	***Low Risk***
C. Service-Based Allocation Across Terrestrial/ Satellite Architecture	This architecture could be phased in and considered an extension to the type of SATCOM/ terrestrial architectures in use today (modest risk)	Not applicable	Need to design and implement new interfaces to SATCOM and terrestrial systems (modest risk)	Need to extend similar architecture in use today to accommodate dual active services across terrestrial and SATCOM systems (Moderate Risk)	***Moderate Risk***

TABLE E–28.—EVALUATION OF HYBRID ARCHITECTURES—RELATIVE BENEFIT

	Factor			Assessment
	Capacity	Efficiency	Cost	
A. Dual GEO/LEO Satellite Architecture	Architecture accommodates communication functionality of COCR	May not be extremely efficient to maintain a SATCOM system and associated capacity as a “hot spare” (may be less efficient than other alternatives)	Use of SATCOM systems alone removes the need to implement new terrestrial infrastructure; however infrastructure to connect to the SATCOM ground network is required	***Low Benefit***
B. Geographic -Based Allocation of Services	Architecture accommodates communication functionality of COCR; however SATCOM allocations may not meet all COCR required performance; may be limited capacity improvement over current/planned implementation	Accommodates transition from existing similar architectures to slowly add capability and efficiency	May not be large efficiency improvement over existing/planned capabilities without significant costs	***Moderate Benefit***
C. Service-Based Allocation Across Terrestrial/ Satellite Architecture	Architecture accommodates communication functionality of COCR; however SATCOM allocations may not meet all COCR required performance	May provide a scenario to best use planned data communication infrastructure (e.g. VDL-2) while adding less critical services over a supplemental SATCOM architecture; this could be a significant benefit	Need to account for new infrastructure to connect to the SATCOM ground network; terrestrial infrastructure could be provided (at least initially and potentially fully) by planned terrestrial-based data link architectures (e.g. VDL-2)	***Moderate Benefit***

The analysis results from the tables above have been summarized into a single condensed table, shown below. Results indicate that there is a potential role for hybrid satellite architectures for provision of aeronautical mobile communications, but a specific role is not entirely obvious. A hybrid architecture that satisfies multiple roles (i.e., provides capacity and emergency backup, such as offered by architectures B and C or a combination of the two) may be desirable. Although in this brief treatment of hybrid alternatives no one architecture is a standout, architectures B and C appear to have greater potential than architecture A.

TABLE E–29.—SUMMARY OF SATCOM HYBRID ARCHITECTURE RESULTS

Architecture Name	Functional Capability	Performance Capability	Cost	Technical Risk	Benefit
A. Dual GEO/LEO Satellite Architecture	MEETS	PARTIALLY MEETS	HIGH	HIGH	LOW
B. Geographic-based allocation of services across terrestrial/satellite architecture	MEETS	PARTIALLY MEETS	MODERATE	LOW	MODERATE
C. Service-based allocation of services across terrestrial/satellite architecture	MEETS	PARTIALLY MEETS	HIGH	MODERATE	MODERATE

E.2.4 Summary And Recommendations

Some limiting factors have been identified for SATCOM systems with regard to availability performance. As a result, the full set of COCR service availability requirements are not likely to be met by Inmarsat SBB (nor Iridium) and would require a highly redundant architecture for custom satellite solutions (with high-cost impacts). Therefore, although these candidates are likely to provide valuable services in specific airspace domains (e.g., oceanic/remote), they are not viable candidates for a general continental solution. It is recommended that there be continued exploration of availability performance as architecture-specific information is made available by satellite service providers. Additionally, these candidates can be analyzed further to explore their role in satisfying oceanic/remote domain requirements.

E.3 C-Band Environment and Applicable Technology Analysis

This section of the appendix describes the C-Band modeling activities. This modeling was conducted to investigate the utility of an industry standard system in the airport surface environment. The system that was chosen for analysis was the IEEE 802.16e Metropolitan Area Network (MAN) interface standard. The IEEE 802.16e standard (referred to as simply the 802.16e standard, or 802.16e henceforth) was chosen as it scored well during the initial phase (technology pre-screening) of the FCS technology investigations.

The rationale for selecting C-Band for the analysis was that the technology is designed to work in the band, it is a band that currently belongs to aviation, the band is currently underutilized, and the application (MAN in an airport environment) and propagation characteristics of the band are well matched. Further, there is increasing motivation for the aeronautical community to protect the current allocation of 5000 to 5250 MHz for ARNS, due in no small part because the band is underutilized, with only 11 civil systems and 29 military systems in the 5030 to 5091 MHz band, but also because there are commercial technologies, already contiguous to the band, that are poised for explosive growth and are actively seeking new spectrum.

E.3.1 802.16 Overview

The 802.16 and is IEEE-developed standard for Wireless MAN. The standard was originally defined for fixed-access only; however, mobility was added by publishing a corrigendum to the standard (known as 802.16e). Some of the advantages of 802.16 are that it:

- Provides very efficient use of spectrum
- Provides high bandwidth, with hundreds of users per channel
- Provides flexible QoS offerings, including
  - Unsolicited grant services for constant bit-rate service flows (SFs)
  - Real-time polling services for real time variable bit rate SFs
  - Non-real-time polling services
  - Best effort
- Supports a wide range of applicable frequencies (up to 66 GHz)
- Provides high data rates for uplink and downlink
- Supports multiple physical interfaces

The 802.16e was developed to provide enhancements to 802.16. To support subscriber stations moving at vehicular speeds. The 802.16e specifies a system for combined fixed and mobile broadband wireless access. 802.16e operation is limited to licensed bands suitable for mobility below 6 GHz; however, other fixed 802.16 subscriber capabilities are not compromised (in these frequency bands). The standard supports a range of physical layers, which are shown below.

E.3.1.1 Overview of Physical Layers

E.3.1.1.1 WirelessMAN-SC™ (IEEE)

This is the original air-interface for 802.16. It is designed to work in LOS environments, with a point-to-multipoint architecture. As shown in table E–30, this physical layer is defined (and applicable) to frequencies in the 10 to 66 GHz range. As a consequence, it is not applicable for use in the extended MLS Band (5.091 to 5.150 GHz). The SC air interface supports communications distances in the range of 31 to 50 miles with data transfer rates up to 70 Mbps. It uses an adaptive-modulation (QPSK, 16-QAM, and 64-QAM) scheme.

TABLE E–30.—802.16 PHYSICAL LAYERS SHOWING THOSE FOR WHICH MOBILITY IS APPLICABLE

Designation	Applicability	Options	Duplexing alternative
WirelessMAN-SC™	10-66 GHz	—	TDD FDD
WirelessMAN-SCa™	below 11 GHz licensed bands	Adaptive Antenna System (AAS) Automatic Repeat Request (ARQ) Space Time Coding (STC) **Mobile**	TDD FDD
WirelessMAN-OFDM™	below 11 GHz licensed bands	AAS ARQ Mesh STC **Mobile**	TDD FDD
WirelessMAN-OFDMA	below 11 GHz licensed bands	AAS ARQ Hybrid ARQ (HARQ) STC **Mobile**	TDD FDD
WirelessHUMAN™	below 11 GHz license-exempt bands	AAS ARQ Mesh STC	TDD

E.3.1.1.2 WirelessMAN-SCa™

Defined for the 2- to 11-GHz band, the WirelessMAN-SCa™ (or SC2 as it is alternatively known) is also a single-carrier modulation. It is designed for non-LOS (NLOS) channels and uses adaptive modulation. Supported modulations include “spread BPSK,” BPSK, QPSK, 16-QAM, 64-QAM, and 256-QAM. Both Time- and Frequency-Division Duplex modes are defined, with uplink being TDMA, and downlink either TDM or TDMA.

E.3.1.1.3 WirelessMAN-OFDM™

The 802.16 orthogonal frequency division multiplexing (OFDM) physical layer is designed for NLOS operation in licensed bands below 11 GHz. It is clearly applicable for use on the airport surface, where measurements have shown large areas that can be characterized as NLOS.[141] The physical layer uses OFDM with a fixed FFT size of 256 carriers. Variable sub-carrier spacing is defined in order to support multiple bandwidths. The rationale for this is the variation in licensed bandwidths throughout the world, for example, the band 3.4 to 3.6 GHz uses channels that are either 3.5 or 7.0 MHz, whereas at 5.725 to 5.850 GHz the channels are 10 MHz.

The physical layer employs scrambling (to ensure equiprobable 1’s and 0’s), Forward Error Correction, block interleaving, symbol modulation, mapping to carriers, and then inverse-fourier transformation to get the time domain waveform. A variable cyclic-prefix is prepended to each OFDM symbol. The purpose of the cyclic prefix is to “collect” the multipath returns, thus eliminating intersymbol interference from channel delay spread. The cyclic prefix can vary between 1/32 and 1/4 of the OFDM symbol duration. Coding includes concatenated Reed-Solomonconvolutional code (mandatory), block turbocoding (optional) or convolutional turbocodes (optional). The OFDM physical layer provides adaptive modulation. Thus, depending on channel conditions, the base station and subscriber station can use BPSK, QPSK, 16-QAM, or 64-QAM. The frequency domain OFDM signal is shown in figure E–107. The 256 carries are divided into guard bands, data carriers, pilot carriers, and a “DC carrier.” A total of 55 carriers are not used (28 on one side and 27 on the other) in order to provide a frequency guard band. There are eight pilot carriers (specified to have slightly more power than the data carriers) and 192 data carriers in the waveform.

The 802.16e corrigendum specifies several changes to the OFDM physical layer. These include downlink (basestation to subscriberstation) sub-channelisation, fast ranging, fast tracking (for power, time, and frequency corrections), and introduction of an open-loop power control mode.

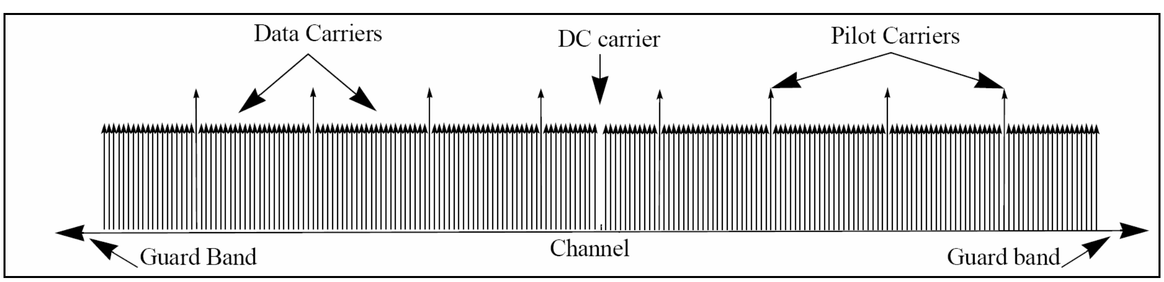


Figure E–107.—802.16 OFDM Physical Layer.

E.3.1.1.4 WirelessMAN-OFDMA

Like the OFDM waveform, this also uses OFDM modulation; however, subsets of carriers are mapped to sub-channels to support multiple access and other features. It was also designed for NLOS operation and supports mobility through the specified changes in the 802.16e corrigendum. OFDMA supports variable bandwidths by changing the FFT definition (as opposed to OFDM where the sub-carrier spacing is changed, but the number of sub-carriers, or FFT definition, remains fixed). OFDMA also provides for dynamic adaptive modulation and uses QPSK, 16-QAM, and 64-QAM. Coding includes tail-biting convolutional coding (mandatory), block turbocoding (optional), or convolutional turbocodes (optional).

E.3.1.1.5 WirelessHUMAN™

HUMAN is an acronym for "high-speed unlicensed metropolitan area network." WirelessHUMAN™ is not really a separate physical interface, rather the standard defines specific system profiles for the SCa, OFDM, and OFDMA physical layers when used in unlicensed bands.

E.3.1.2 Relationship to WiMAX

The WiMAX Forum is a consortium of over 300 member companies. The purpose of the WiMAX Forum is "to facilitate the deployment of broadband wireless networks based on the IEEE 802.16 standard by ensuring the compatibility and interoperability of broadband wireless equipment".[142] The mechanism that has been adopted to ensure interoperability of IEEE 802.16 and other interoperable (ETSI HiperMAN) systems is to:

- Define Protocol Implementation Conformance Statements (PICS) to which commercial equipment will be developed
- Host interoperability events (plugfests)
- Define test suites (structure and purpose), conduct tests, and certify PICS compliant equipment

The PICS are used to reduce the breadth of the IEEE 802.16 standard so that interoperability can be achieved and are based on market requirements. At this time, PICS are defined for fixed-broadband access (known as "fixed" WiMAX) and are being developed for "Mobile" WiMAX. The system profiles for "Fixed" WiMAX all use the 802.16 OFDM physical layer and are shown in table E–31.

TABLE E–31.—WIMAX FORUM FIXED BROADBAND ACCESS PROFILES

Frequency Band	Duplexing	Channelisation (MHz)
3400 – 3600	TDD	3.5
		7.0
	FDD	3.5
		7.0
5725 – 5850	TDD	10

It is expected that the "Mobile" WiMAX profiles will be based on the OFDMA physical layer, will have 5 and 10 MHz defined bandwidths, and provision for the use of MIMO and single antenna base stations.

The purpose of discussing the WiMAX Forum in this appendix is to note that it is extremely likely that all commercially available 802.16 equipment will be WiMAX certified; hence, it will operate in one of the defined frequency bands, have either OFDM or OFDMA physical layer and use defined duplexing and channelisation parameters. To contrast, the IEEE 801.16 is quite flexible by design and the WiMAX Forum PICS are quite inflexible by design. The aviation community will have to decide whether it would like to leverage the commercial momentum of the WiMAX products (for instance Intel has a chipset that

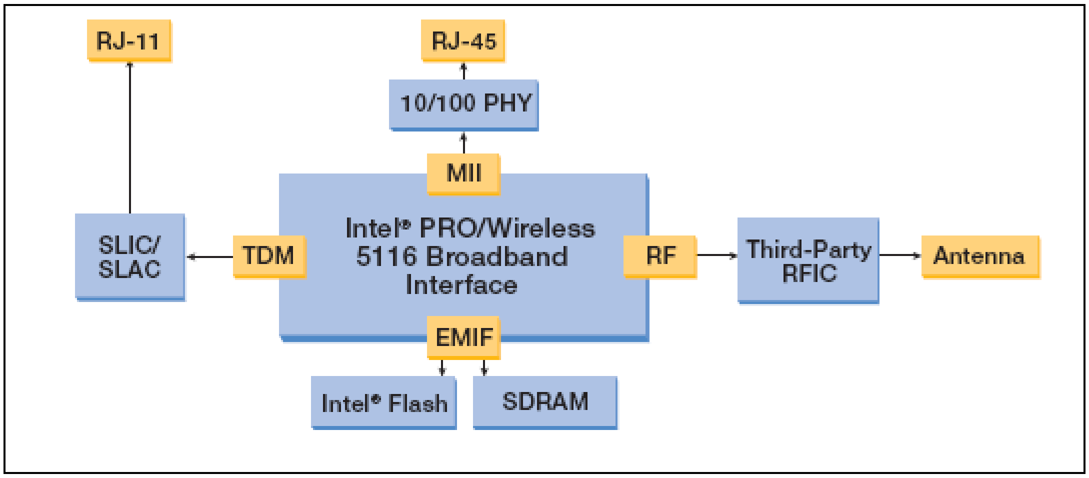


Figure E–108.—Notional 802.16 Radio Using Chipsets.[143]

implements the 802.16 OFDM physical layer[144] in accord with the WiMAX Forum PICS) or if it wants to customize the IEEE 802.16 standards to suit the specific requirements of aviation. Some customization will clearly be required, as the frequency band that is being suggested for aviation use is 5.091 to 5.150 GHz, which is clearly different from the defined bands for "Fixed" WiMAX (as can be seen in table E–31) and is certain to be different than the defined profiles for "Mobile" WiMAX as well. However, the use of either OFDM or OFDMA with the duplexing and other parameters specified by the WiMAX forum would enable the use of (relatively inexpensive) chipsets such as the Intel chip referenced above. Figure E–108 shows how an 802.16 radio could be developed relatively inexpensively using commercially available chipsets.

E.3.2 802.16 Modeling

To model 802.16, a suitable physical layer for the airport environment must first be selected. From table E–30, the SCa, OFDM, and OFDMA physical layers all support mobility; however, from the discussion on the WiMAX Forum, it seems appropriate to select either OFDM or OFDMA for analysis. A brief summary of the differences between the two (that impact mobility performance) is provided below.

- **HARQ:** the standard indicates that this is an OFDMA option only (paragraph 6.3.17). Since HARQ provides a time-diversity element that is an effective mitigator to mobility-induced fading, it seems that OFDMA will be more robust that OFDM in fading channels.
- **Use of Fast Feedback Channel (CQICH):** the standard indicates this is an OFDMA option only (paragraph 6.3.17.4). The use of fast feedback, when combined with adaptive modulation and coding, is an effective mitigator to mobility induced fading, so again, OFDMA is likely more robust than the OFDM physical layer (as defined) in a fading channel.
- **Use of Diversity Sub-Carrier Permutations**: the OFDMA physical layer uses sub-carrier permutations to form sub-channels. This can provide a frequency diversity advantage when compared to the OFDM physical layer.

Clearly, better mobility performance is expected from OFDMA than OFDM, and the WiMAX Forum "Mobile" WiMAX profiles are all expected to adopt the OFDMA physical layer. The OFDM physical layer was selected for analysis, as it seems that if good performance can be predicted for OFDM by inference the OFDMA physical layer would also work well. Further, as mentioned above, there are commercially available chipsets for the 802.16 OFDM physical layer currently available. Since a logical next step to this research would be prototype implementations and trials in the band, and noting that

OFDM (due to the aforementioned chipset) is more amenable to prototype equipment development, this seems to be a reasonable decision.

In addition to selecting the physical layer, several other parameters have to be established. These include the duration of the cyclic prefix, the spacing between frequency carriers, the modulation type (or types) and the duration between OFDM preamble symbols. As defined in the standards,

> Four primitive parameters characterize the OFDM symbol:
> BW is the nominal channel bandwidth.
> N_{used} is number of used sub-carriers.
> n is sampling factor. This parameter, in conjunction with BW and N determines the sub-carrier spacing and the useful symbol time. Required values of this parameter are specified in 8.3.2.4.
> G is the ratio of CP time to "useful" time.[145]

Table E–32 shows the parameters and the values that were associated with those parameters in the simulation of 802.16 OFDM.

TABLE E–32.—OFDM PARAMETERS SELECTED FOR ANALYSIS

Parameter	Selected Parameter Value
N_{FFT}	256
BW	10 MHz
N_{Used}	200
n	n = 57/50 (standard specifies this for channel bandwidths that are a multiple of 2.0 MHz)
G	1/4
Modulation Type	16 QAM
OFDM Frame Duration	2.5 ms

E.3.2.1 802.16e Modeling

The process for modeling the 802.16e OFDM physical layer was to:

1. Select a modeling environment
2. Implement the 802.16e transmitter functions and validate against known test vectors
3. Implement additional transmitter functions required to simulate system and validate by inspection of output signal spectrum
4. Implement 802.16e receiver and validate end-to-end performance in an Additive White Gaussian Noise (AWGN) channel with known results
5. Implement a fading channel for which published results are available, implement the receiver channel equalization, and validate model performance
6. Introduce the airport surface channel model as defined by Ohio University research and published in "Wireless Channel Characterization in the 5 GHz Microwave Landing System Extension Band for Airport Surface Areas"

Step 1: Select a modeling environment

MATLAB Simulink® (The Mathworks, Inc.) was selected for modeling the 802.16e OFDM physical layer. To quote the MathWorks product page: "*Simulink is a platform for multidomain simulation and model-based design for dynamic systems. It provides an interactive graphical environment and a customizable set of block libraries, and can be extended for specialized applications*".[146] Simulink provides a very powerful extension to MATLAB for modeling and simulation of many types of systems. It is especially useful for simulating communications systems.

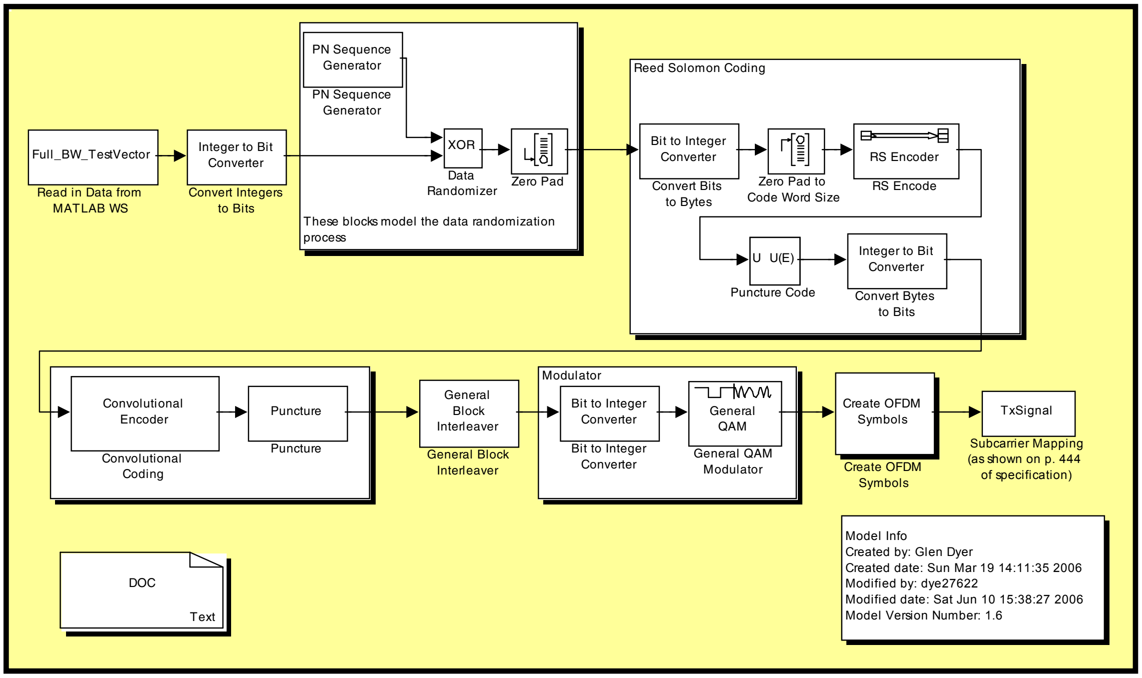


Figure E–109.—MATLAB Simulink® 802.16e Transmitter Model for Validation.

Step 2: Implement the 802.16e transmitter functions and validate against known test vectors

The 802.16e standard provides test vectors for specific instantiations of the physical layer. For example, a set of test vectors (input data, after randomization, after coding, and after modulation) for the rate ¾ (concatenated Reed-Solomon and convolutional coding) QPSK OFDM implementation is provided. To ensure proper transmitter implementation, the transmitter was modeled in accord with the standard for this specific configuration, and the model output was checked against the published test vectors. Figure E–109 shows the MATLAB Simulink model that was developed and subsequently checked using the test vectors supplied in the standard.

After entering the test vectors published in the standards into the MATLAB workspace through a cut-and-paste operation, the operation of the Simulink modeled 802.16e transmitter could be validated at every major functional point. Figure E–109 shows the complete model where the input vector is read in from the MATLAB workspace (named "Full_BW_TestVector") and the output is written to the MATLAB variable "TxSignal." The variable "TxSignal" was then compared to the specified test vector and was found to be identical.

Step 3: Implement additional transmitter functions required to simulate system and validate by inspection of output signal spectrum

The transmitter model that is shown in figure E–109 is not complete. Additional elements are required for proper transmitter modeling. First, the OFDM carriers must be inverse-Fourier transformed and then a cyclic prefix must be prepended to the OFDM symbol. Also, the OFDM burst structure must be created using appropriate preamble and data sequences. All of these additional elements were modeled, and the resultant output signal spectrum is shown in figure E–110. A comparison of the ideal spectrum shown in figure E–107 with the simulated spectrum that is shown in figure E–110 shows that there is a guard band, data carriers, pilot carriers, and a DC null all in the expected locations.

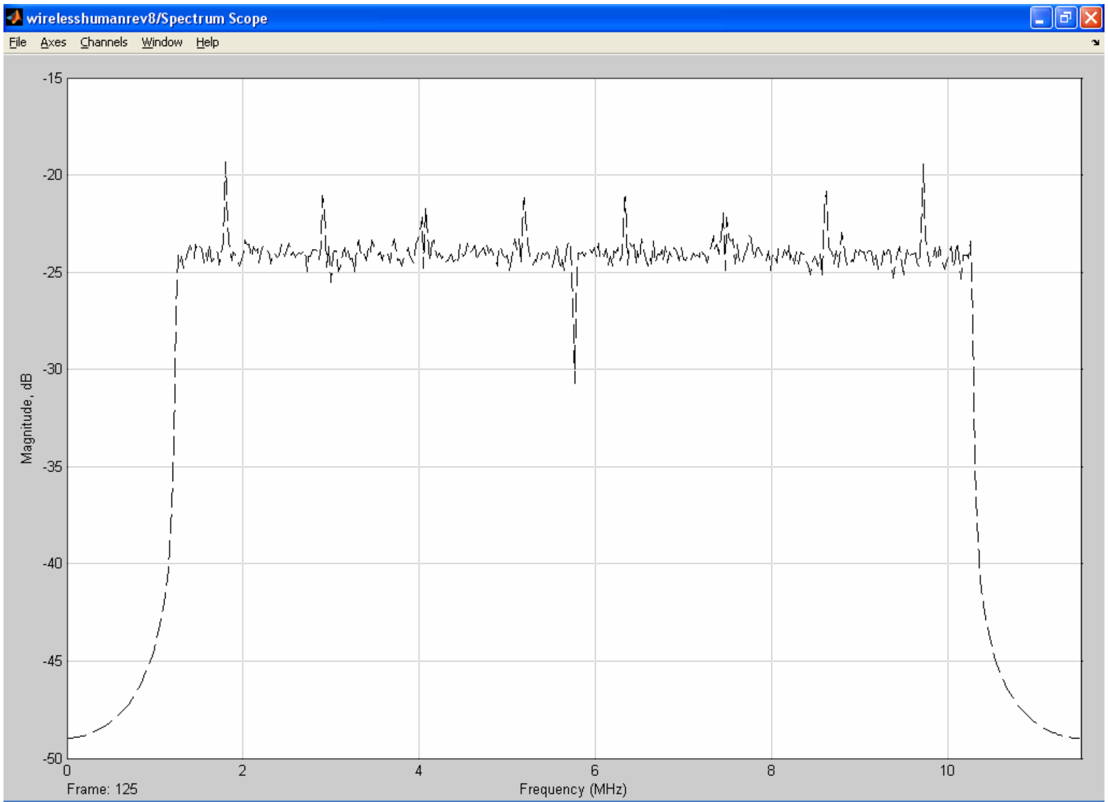


Figure E–110.—802.16e Transmitter Model Output Signal Spectrum.

Step 4: Implement 802.16e receiver and validate end-to-end performance in an Additive White Gaussian Noise (AWGN) channel with known results

The receiver implementation is in essence an inversion of all the transmitter functions with some important caveats. Several important receiver functions have little to do with the transmitter operations but have a large impact on receiver performance. These include carrier tracking, frame synchronization, and channel estimation. Of these, only the channel estimation functions were modeled in this simulation.

The 802.16e receiver modeling was performed in a sequential fashion. First, a receiver model was constructed that reverses all of the elements of the transmitter, and its performance was validated using the AWGN channel. Second, a known channel model (the "SUI-1") was introduced (step 5 of our modeling process). Stanford University Interim, or SUI, models were used for evaluation of suggested 802.16e physical layer modifications during development of the standards, and published results are available for expected receiver performance. This step was performed because obtaining good results with the SUI channel requires implementation of a receiver channel equalization function, and using known results provides a validation of the equalizer implementation. Once good results for known impairments were achieved, the model was considered satisfactory for use in evaluation of unknown impairments, that is, the Ohio University Airport Surface Channel model (step 6 of our modeling process).

Figure E–111 shows the initial receiver model incorporated into the context of an end-to-end simulation. Operations are sequential, and are an exact inverse of the related transmitter functions. Hence, we first extract the data symbols from the OFDM waveform. Then we demodulated the QAM waveform, deinterleave, decode (first Viterbi, then Reed-Solomon) and finally reverse the bit scrambling operation of the transmitter.

The model shown in figure E–111 was used to predict the performance of the 802.16e 16-QAM modulation in an AWGN channel. Results are shown in figure E–112. Simulations were used to predict performance both with and without coding. Good agreement was obtained with theory for the case of no coding, as can be seen in the figure. The coding gain of the concatenated convolutional and Reed-

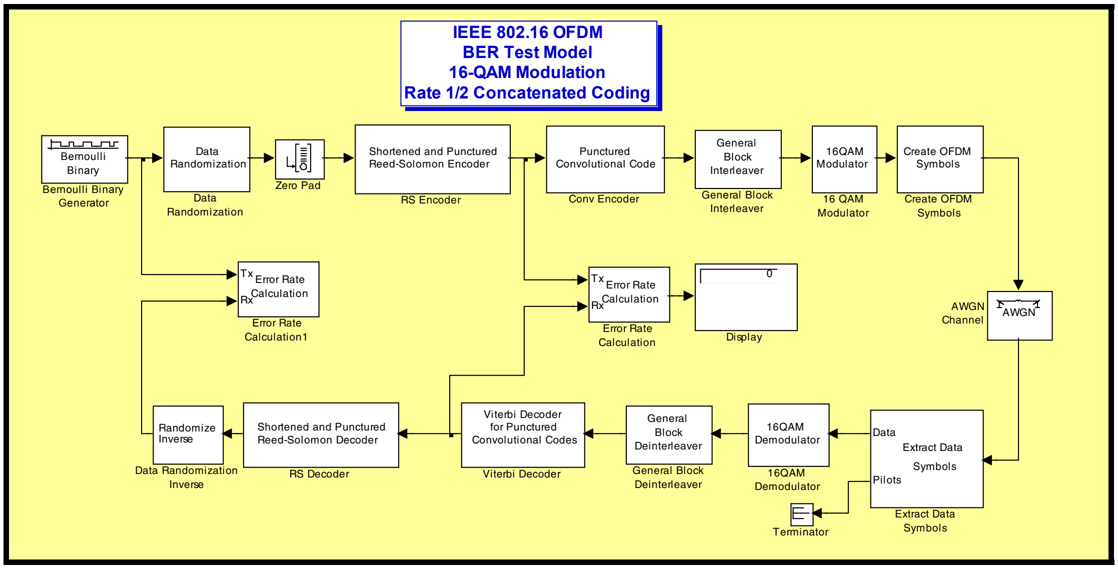


Figure E–111.—802.16e End-to-End Model

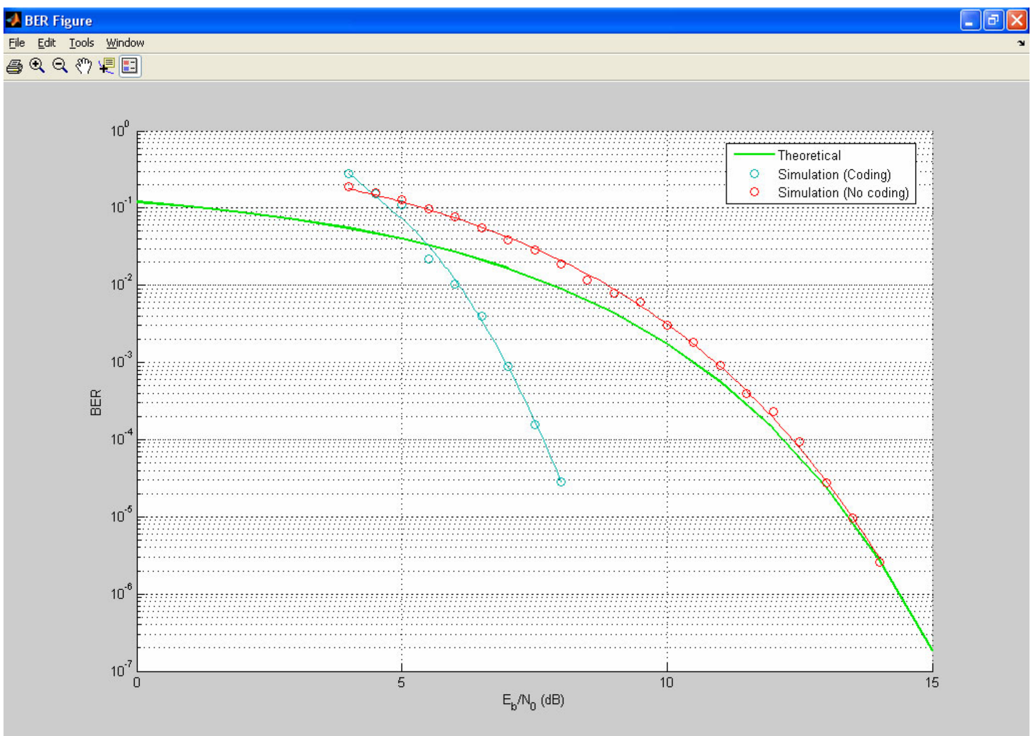


Figure E–112.—Theory and Simulation Results for 16-QAM With and Without Coding.

Solomon codes is substantial, and an inspection of the results indicates that for raw channel BERs less than about $7 \bullet 10^{-3}$ the overall performance of the system will be quite good (that is, the corrected BER will be less than $1 \bullet 10^{-5}$). In order to save computational time, many of the simulations in steps 5 and 6 omitted the channel coding. This is a common practice in simulation work and substantially speeds simulation development and testing.

Step 5: Implement a fading channel for which published results are available, implement the receiver channel equalization, and validate model performance

To validate the channel equalizer development, a set of published results for expected receiver performance in a multipath environment was obtained.[147] The channel models that were used in developing the 802.16e standards are known as the SUI models. A set of six typical channels are defined over three terrain types that are typical of the continental U.S. (SUI Models are defined for all three terrain types, see table E–33):

- Category A—Hilly terrain with moderate-to-heavy tree densities
- Category C—Mostly flat terrain with light tree densities
- Category B—Either mostly flat terrain with moderate-to-heavy tree densities, or hilly terrain with light tree densities

TABLE E–33.—TERRAIN TYPE AND APPLICABLE SUI CHANNEL MODEL[148]

Terrain Type	SUI Channels
C	SUI-1, SUI-2
B	SUI-3, SUI-4
A	SUI-5, SUI-6

The Ward paper presents results for 64-QAM and 16-QAM over the SUI-1 channel. The SUI-1 channel model is a three-tap model that is applicable when neither the base station nor the subscriber stations are moving. Hence, the Doppler is rather small (0.4 Hz) and represents the motion of scatterers in the channel. The SUI-1 model parameters are shown in table E–34.

TABLE E–34.—SUI-1 CHANNEL MODEL PARAMETERS

Tap	Fading Process	Other Parameters
Tap 1	Ricean	K-factor of 4
Tap 2	Rayleigh	0.4 μs delay, -15 dB gain
Tap 3	Rayleigh	0.8 μs delay, -20 dB gain

The SUI-1 channel was implemented in Simulink, and placed between the 802.16e transmitter and receiver (after the AWGN block shown in figure E–111). The SUI-1 channel effects can be immediately seen by looking at the 802.16e spectrum before and after the channel. Figure E–113 shows this.

Coherent demodulation (as is required for 16-QAM) requires estimation of the channel time and frequency response. OFDM systems use both time and frequency pilot information to allow channel estimation. Both “Block Type” and “Comb Type” pilots are employed. “Block Type” pilot structures refer to schemes whereby at regular instances in time, all of the frequency carriers are used to convey pilot information; that is, a “block” of pilots is sent at regular intervals. In “Comb Type” systems, some frequency carriers always have pilot information at every instance in time. The 802.16e uses “Comb Type” pilots (as is clearly shown in figure E–109), but also uses a known synchronization sequence every (configurable, but in our simulations set to 90) data blocks to frame the data bursts.

The optimal algorithm for equalization is to use a two-dimensional Wiener filter. This is complex and computationally expensive. Several suboptimal algorithms exist and their performance has been documented extensively. For Block Type pilot arrangements, there are least square (LS), minimum mean-square error (MMSE), and modified MMSE equalization schemes. For Comb Type pilot schemes, there are LS estimator with one-dimensional interpolation, the maximum likelihood (ML) estimator, and the parametric channel modeling-based (PCMB) estimator equalization schemes. Some recommended channel estimation schemes (from both a complexity and performance standpoint) are shown in figure E–114.

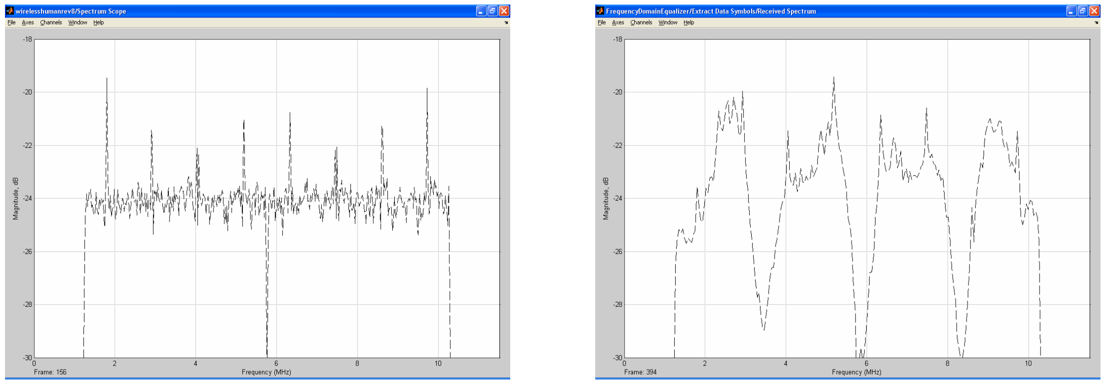


Figure E–113.—802.16e Spectrum Before (left) and After (right) SUI-1 Channel.

Table 3. Recommended OFDM System Channel Estimation Schemes for Different Scenarios and Requirements

Scheme	Scenario	Pilot	Complexity	2^{nd} Order Statistics of Channel	Performance
OLR-MMSE	Slow fading channel	Block-type	Moderate	Needed	Good
LS with LPI	Middle and fast fading channel	Comb-type	Low	Not needed	Good
PCMB			High	Needed	Very good

Figure E–114.—Complexity and Performance of Several Channel Estimation Schemes.[149]

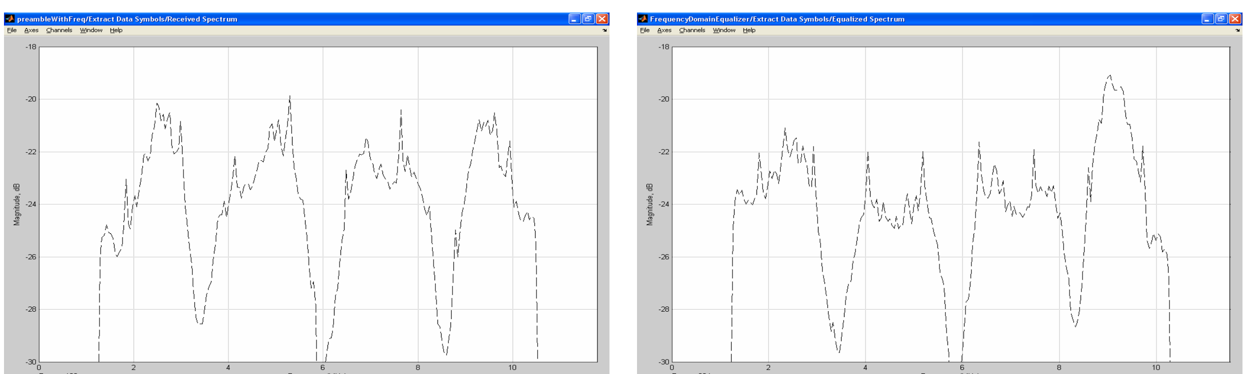


Figure E–115.—802.16e Spectrum After SUI-1 Channel (left) and After LS LPI Equalization (right).

A least squares estimator with Low Pass Interpolation (LS LPI) was selected as an element of the channel estimation technique. To use this technique, one first estimates the channel frequency response at the pilot symbol locations, and then uses low pass interpolation to estimate the frequency response at all intermediate locations. This is not sufficient to equalize the effects of the channel in toto, as the pilot locations are rather sparse in the 802.16e symbol structure. The 802.16e spectrum after the SUI-1 channel and after the LS LPI equalization is shown in figure E–115. Clearly, the equalization has worked well in the pilot locations, and many of the data locations are closer to their original values, but overall this would not be a completely effective scheme without additional processing.

The additional information that is required can be obtained by exploiting the 802.16e framing. As defined in the standard, the OFDM physical layer uses frame-based transmission. Each (downlink) protocol data unit (PDU) starts with a long preamble, which is used for synchronization. All preambles are structured as either one of two OFDM symbols. The OFDM symbols are defined by the values of the composing sub-carriers. Since the structure and periodicity of these preambles is known, they can also be used for channel estimation purposes. There is some flexibility in the standard in terms of the periodicity of the preamble information. In order to provide the maximum robustness, the preamble information was repeated at the highest allowable rate, which is every 2.5 ms.

The simulation was modified to incorporate the preamble information into the channel equalization. Modifications were required to the transmitter so that frames of OFDM data could be created (as opposed to symbol-by-symbol processing of the original simulation). Each frame was preceded by the (defined) synchronization sequence. A new equalizer was designed and implemented in the receiver as well. Figure E–116 shows the 802.16e spectrum before and after equalization.

The complete simulation was run over a range of bit energy to noise-power density (EbNo) values. Figure E–117 shows the simulation results (on the right) compared to published results. Since the published results used no coding, the simulation was run without either convolutional or Reed-Solomon coding. Results are shown for the LS LPI equalization only, and then for including the 802.16e synchronization sequence information. The simulated results are clearly within about 1 dB of the theoretical modulation performance in noise, which is slightly better than the published results (also achieved via simulation). As an example, the published results show a BER of 10^{-4} for a 13.3 dB EbNo whereas our simulations show the same result at an EbNo of 12.5 dB. This was felt to be a validation that the designed equalizer was functioning.

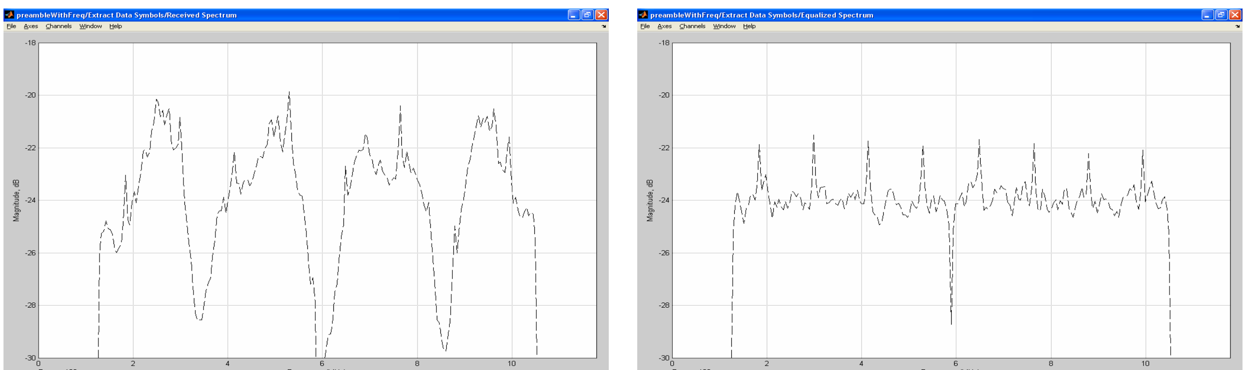


Figure E–116.—802.16e Spectrum After SUI-1 Channel (left) and After Equalization (right).

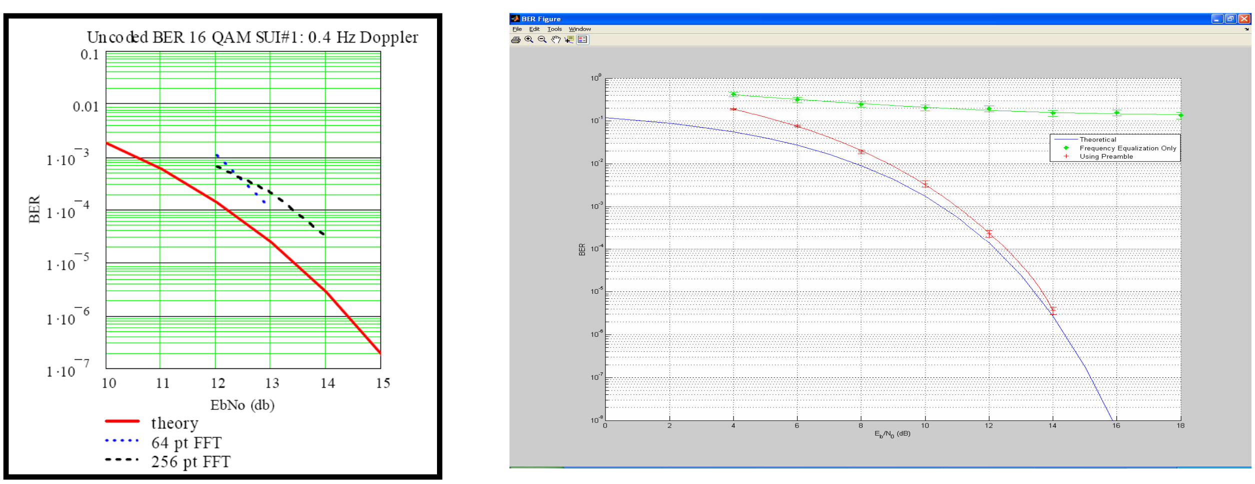


Figure E–117.—Published Results (left) and Simulated Results (right) for SUI-1 Channel (802.16e 16-QAM Performance).

Before discussing the results of step six of the modeling process, a brief description of the Ohio University C-Band channel models is provided in the next section. After this discussion, the steps required to incorporate the C-Band channel model(s) into the 802.16e simulation are described, as well as the simulated results and suggested further research.

E.3.3 C-Band Channel Model

In order to assess 802.16e performance in an airport environment, a realistic model of the communications channel is required. This model must accurately reflect the small-scale fading environment so that waveform performance can be assessed. Further, the model should accurately categorize delay spread (assess whether cyclic prefix is adequate). Finally, the model should accurately categorize Doppler Power spectrum (determines coherence time of channel and assesses adequacy of pilot symbol structure).

Ohio University has conducted an airport surface measurement campaign for NASA Glenn Research Center.[150] The measurement campaign provides wireless channel characterization of the MLS Extension band (5.091 to 5.150 GHz) and utilized the sliding correlator technique for measuring the channel impulse response at a number of airports in the United States. The measurements included mobile, point-to-point, and emulation of communication relay (both Tx and Rx on airport surface). The measurement report provides statistics on delay spread, coherence bandwidth, path loss, tap amplitudes, number of taps, and correlation between taps. An adapted channel model (as described in the report and subsequent correspondence) was used for this evaluation.

Analysis of the measurements (known as channel sounding) has provided a taxonomy of airport surface channels that can be characterized by the type of channel (LOS, NLOS, and NLOS specular) as well as the type of airport (small, medium, and large).[151] Since the large airport model (as defined in the referenced report) is the most severe (in terms of time dispersion or number of taps in the reference model tapped delay line) it was selected for analysis. In the large airport model, the NLOS region has by far the most time dispersion and was also selected for analysis. (The selection methodology that was employed is conservative, with a rationale that if good performance could be predicted for the most severe expected channel, then by extension good performance would be expected in less severe channels.)

Dr. Matolak defines varying fidelity models, specifically high-fidelity and sufficient-fidelity channel models.[152] The high-fidelity model is directed towards academic applications and provides a comprehensive and highly accurate depiction of the channel (at the cost of implementation complexity). The sufficient-fidelity model provides a practical emulation of the channel with moderate implementation complexity. The sufficient fidelity model was selected for simulation.

The final element of the channel model taxonomy is the channel bandwidth. As the 802.16e physical layer that is being simulated has a 10 MHz bandwidth, the 10 MHz bandwidth channel model parameters were used in this analysis. The parameters for this particular model were not published at the time of this analysis. The required parameters (described in detail below) were obtained via private correspondence with Dr. Matolak.[153]

For the sufficient fidelity, large airport, NLOS channel model, the suggested channel model parameters include tap persistence, number of taps, fading processes, and tap correlations. The tap persistence accounts for the finite lifetime of propagation paths and is modeled as a random “switching” process, or Markov chain. The suggested persistence process parameters are shown in table E–35.

TABLE E–35.—SUGGESTED PERSISTENCE PROCESS PARAMETERS
FOR LARGE AIRPORT, NLOS, 10-MHz MODEL

Tap Index	Steady State Probability for State 1	Steady State Probability for State 0	Transition Probability (P_{00})	Transition Probability (P_{01})	Transition Probability (P_{10})	Transition Probability (P_{11})
1	1.0000	0	NaN	NaN	0	1.0000
2	0.8794	0.1206	0.1975	0.8025	0.1101	0.8899
3	0.7890	0.2110	0.3258	0.6742	0.1803	0.8197
4	0.7747	0.2253	0.3301	0.6699	0.1949	0.8051
5	0.7519	0.2481	0.3363	0.6637	0.2191	0.7809
6	0.7437	0.2563	0.3599	0.6401	0.2206	0.7794
7	0.7288	0.2712	0.3789	0.6211	0.2310	0.7690
8	0.7102	0.2898	0.4013	0.5987	0.2444	0.7556
9	0.7060	0.2940	0.4063	0.5938	0.2471	0.7529
10	0.6930	0.3070	0.4324	0.5676	0.2512	0.7488
11	0.7065	0.2935	0.4052	0.5948	0.2472	0.7528
12	0.7000	0.3000	0.3868	0.6132	0.2626	0.7374
13	0.6798	0.3202	0.4453	0.5547	0.2614	0.7386
14	0.6992	0.3008	0.4067	0.5933	0.2551	0.7449

The persistence process is simulated by implementing a Markov chain. When implemented, the existence of certain taps is in essence a random variable. Since it can be noted that the absence of a tap does not impair signal performance but rather helps, this element of the channel model was not simulated.

Other model parameters include the number of taps and their fading statistics (usually modeled as a random process). Table E–36 shows the suggested values for the random process, tap energy, and shape factor (Weibull process) or Nakagami m parameter value. The channel model that was implemented in Simulink does not use either Weibull or Nakagami random processes. Rather, a Rayleigh process is used on all taps, with the average tap energy as shown in table E–36. Unlike other assumptions that were made in this analysis, this is not likely to be a conservative simplification. The channel model parameters were not available until the near the end of the project, and this simplifying assumption was make in the spirit of expediency. Further analysis of the ramifications of this assumption is warranted and recommended.

TABLE E–36.—AMPLITUDE STATISTICS FOR LARGE AIRPORT, NLOS, 10 MHz MODEL

Index	Weibull Shape Factor (*b*)	Tap Energy	Alternative Distribution Parameter (Nakagami)
1	2.1	0.5273	m=1.2
2	1.58	0.0605	m=0.72
3	1.56	0.0382	m=0.72
4	1.61	0.0346	m=0.74
5	1.63	0.0315	m=0.76
6	1.57	0.0310	m=0.73
7	1.6	0.0302	m=0.74
8	1.67	0.0276	m=0.79
9	1.66	0.0266	m=0.78
10	1.68	0.0248	m=0.8
11	1.65	0.0262	m=0.77
12	1.66	0.0260	m=0.78
13	1.75	0.0234	m=0.84
14	1.72	0.0230	m=0.83

Finally, Dr. Matolak’s research indicates that the tap fading processes are correlated. The correlation matrix of table E–37 is suggested for the large airport, NLOS 10 MHz channel model. The impact of the correlation in fading is to reduce the amount of attainable time diversity, which is not a feature that the modeled implementation of 802.16e leverages. Accordingly, the time correlation of fading between taps was not modeled.

TABLE E–37.—SUGGESTED TAP CORRELATION MATRIX FOR THE SUFFICIENT FIDELITY, LARGE AIRPORT, NLOS 10-MHz MODEL

i,j	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.0000	0.5918	0.6812	0.5749	0.6441	0.6502	0.8756	0.7405	0.7231	0.5870	0.7161	0.5807	0.5496	0.9924
2	0.5918	1.0000	0.4184	0.3755	0.5485	0.4209	0.4793	0.5451	0.6644	0.9408	0.7814	0.6817	0.8126	0.4801
3	0.6812	0.4184	1.0000	0.5666	0.7584	0.5592	0.4585	0.8646	0.5190	0.8350	0.7176	0.5476	0.5406	0.5982
4	0.5749	0.3755	0.5666	1.0000	0.9978	0.8270	0.5931	0.3813	0.5177	0.5171	0.3701	0.4382	0.9092	0.5384
5	0.6441	0.5485	0.7584	0.9978	1.0000	0.9321	0.7170	0.6391	0.8684	0.7690	0.8450	0.9917	0.8419	0.6710
6	0.6502	0.4209	0.5592	0.8270	0.9321	1.0000	0.7656	0.6292	0.3860	0.6396	0.7282	0.6136	0.5330	0.3691
7	0.8756	0.4793	0.4585	0.5931	0.7170	0.7656	1.0000	0.4566	0.6887	0.7423	0.4230	0.3845	0.4437	0.9722
8	0.7405	0.5451	0.8646	0.3813	0.6391	0.6292	0.4566	1.0000	0.3898	0.4199	0.7568	0.7600	0.7588	0.6000
9	0.7231	0.6644	0.5190	0.5177	0.8684	0.3860	0.6887	0.3898	1.0000	0.7998	0.6423	0.5593	0.6839	0.5689
10	0.5870	0.9408	0.8350	0.5171	0.7690	0.6396	0.7423	0.4199	0.7998	1.0000	0.5163	0.5457	0.6479	0.6471
11	0.7161	0.7814	0.7176	0.3701	0.8450	0.7282	0.4230	0.7568	0.6423	0.5163	1.0000	0.4338	0.5805	0.8398
12	0.5807	0.6817	0.5476	0.4382	0.9917	0.6136	0.3845	0.7600	0.5593	0.5457	0.4338	1.0000	0.6277	0.6282
13	0.5496	0.8126	0.5406	0.9092	0.8419	0.5330	0.4437	0.7588	0.6839	0.6479	0.5805	0.6277	1.0000	0.8564
14	0.9924	0.4801	0.5982	0.5384	0.6710	0.3691	0.9722	0.6000	0.5689	0.6471	0.8398	0.6282	0.8564	1.0000

E.3.4 Modeling Results and Suggested Further Research

The adapted Ohio University channel model that was used in this simulation had the parameters that are shown in table E–38.

TABLE E–38.—AIRPORT SURFACE CHANNEL MODEL PARAMETERS (AS SIMULATED)

Tap Index	Fading Process	Tap Energy	Relative Delay
1	Rayleigh	0.5273	-
2	Rayleigh	0.0605	0.1 μs
3	Rayleigh	0.0382	0.2 μs
4	Rayleigh	0.0346	0.3 μs
5	Rayleigh	0.0315	0.4 μs
6	Rayleigh	0.0310	0.5 μs
7	Rayleigh	0.0302	0.6 μs
8	Rayleigh	0.0276	0.7 μs
9	Rayleigh	0.0266	0.8 μs
10	Rayleigh	0.0248	0.9 μs
11	Rayleigh	0.0262	1.0 μs
12	Rayleigh	0.0260	1.1 μs
13	Rayleigh	0.0234	1.2 μs
14	Rayleigh	0.0230	1.3 μs

The 802.16e OFDM performance in this channel was simulated for a range of EbNo values. Coding was not included in the simulations, so the correction between raw and coded BER that is suggested in figure E–114 should be applied to the results to get insight into the predicted technology performance that is shown in figure E–118. In the figure, results for various maximum Doppler are shown. The maximum Doppler correspond to velocities of 2, 20, and 100 mph. Recall from the discussion of figure E–114, for raw channel BERs less than about $7 \bullet 10^{-3}$ the overall performance of the system is expected to be quite good (that is to say that the corrected BER will be less than $1 \bullet 10^{-5}$). Hence, the results shown in figure E–118 show no real degradation in system performance for velocities of 2 and 20 mph. Some degradation (on the order of 1.5 dB) is shown when the aircraft velocity is as high as 100 mph.

In an effort to assess 802.16e performance in the movement area (i.e., what is assumed to be a LOS region of the airport surface), a simpler channel model was implemented. This model presumes Ricean fading, with a K factor of 13 dB. The results of simulating the 802.16e OFDM physical layer in this environment are shown in figure E–119. The Doppler values that are plotted correspond to 20, 100, and 130 mph. Note that the curve labeled "theoretical" corresponds to expected performance of 16-QAM in AWGN. From both figures E–118 and E–119, the expected performance of 802.16e on an airport surface is quite good. Recommendations for further study include:

- Increase the fidelity of the channel model to include Weibull (or Nakagami) fading processes and the correlation between taps
- If poor performance results from the step above, model the performance of 802.16e using features that would enhance system performance, including HARQ, fast feedback, diversity sub-carrier permutations, space-time coding, MIMO, and convolutional turbocodes

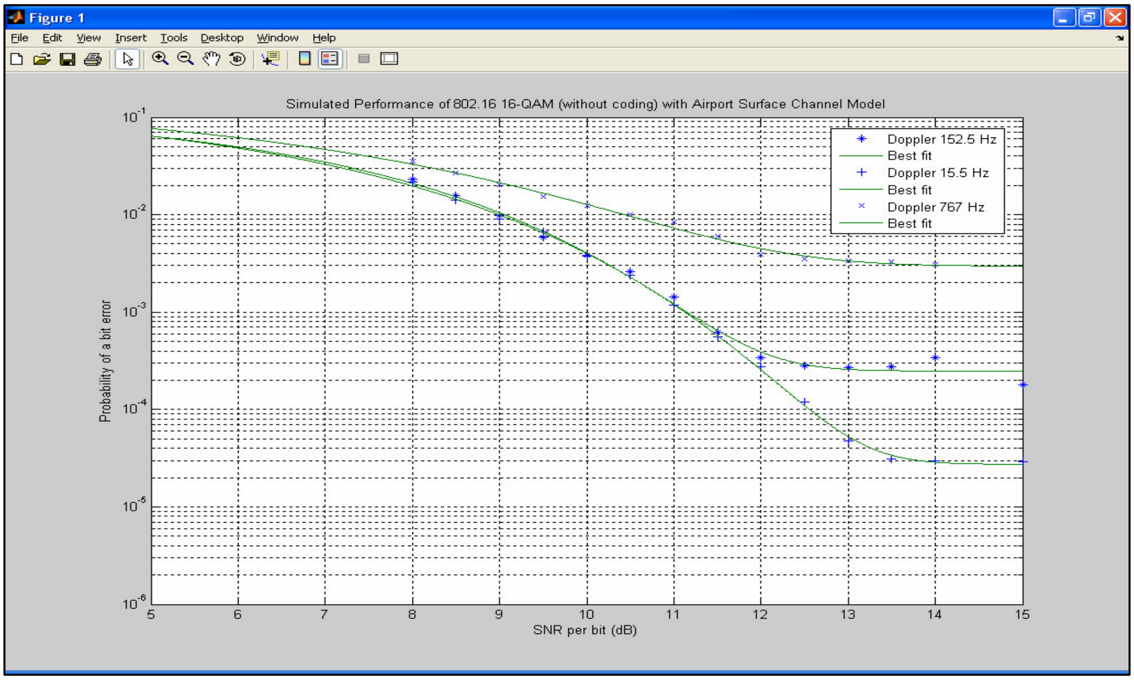


Figure E–118.—Simulated 802.16e 16-QAM Performance Over Large Airport, NLOS, 10-MHz Channel.

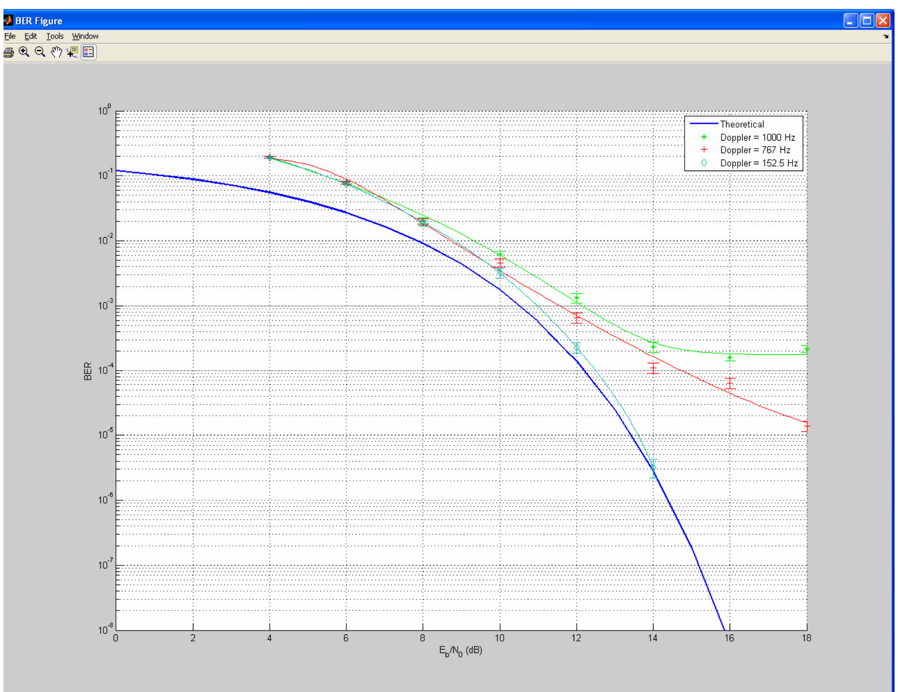


Figure E–119.—Simulated 802.16e 16-QAM Perfomance in LOS Areas of Airport Surface.

APPENDIX F. LIST OF ACRONYMS AND ABBREVIATIONS

The following list identifies acronyms and abbreviations used throughout this report.

1G	1st generation cellular
1x	Single Carrier
2G	2nd generation cellular
3G	3rd generation cellular
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
3x	Multi-Carrier
4G	4th generation cellular
AAC	Airline Administrative Communications
ACARS	Airborne Communications and Reporting System
ACELP	Algebraic Code Excited Linear Prediction
ACP	Aeronautical Communications Panel
ADL	Airport Data Link
ADS-B	Automatic Dependent Surveillance Broadcast
AEEC	Airlines Electronic Engineering Committee
Aero-BGAN	Aeronautical Broadband Global Area Network
AES	Airborne Earth Station
AHP	Analytical Hierarchy Process
AI	Air Interface
AJ	Anti-jam
AM(R)S	Aeronautical Mobile (Route) Service
AMR	Adaptive Multi-Rate (type of codec)
AMSC	American Mobile Satellite Corporation
AMSS	Aeronautical Mobile Satellite Services
ANG	Air National Guard
ANSI	American National Standards Institute (www.ansi.org)
AOC	Air Operations Center
AOC	Airline Operational Control
AP	Access Point
APC	Airline Passenger Communications
APCO	Association of Public-Safety Communications Officers
APIM	ARINC IA Project Initiation/Modification
ARINC	Aeronautical Radio, Inc.
A-SMGCS	Advanced Surface Movement and Guidance System
ATCRBS	Air Traffic Control Radio Beacon System
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Services
AUC	Authentication Center
AVLC	Aviation VHF Link Control
BA	Base Audio
BC	Base Control
BE	Best Effort Service
BER	Bit Error Rate
BGAN	Broadband Global Area Network

BLOS	Beyond LoS
BOC	Billing Operations Center
BPSK	Binary Phase Shift Keying
BR	Base Radio
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
B-VHF	Broadband VHF
C/N	Carrier/Noise power ratio measured in dB
C4FM	Constant Envelope 4-Level Frequency Modulation
CAA	Civil Aviation Authority
CANTCO	Can't Comply
CBB	Connexion By Boeing
CCI	Co-channel Interference
CCK	Complementary Code Keying (RF modulation)
CDMA	Code Division Multiple Access
CLI	Calling Line Identification
CLNS	Connectionless Network Service
CM	Configuration Management
CMU	Communications Management Unit
CNS	Communication, Navigation, Surveillance
CODEC	Combined Coder and Decoder
COFDM	Coded Orthogonal Frequency Division Multiplexing
CON	Console
CONS	Connection Oriented Network Service
CPDLC	Controller Pilot Data Link Communications
CQPSK	Compatible Differential Offset Quadrature Phase Shift Keying
CRC	Cyclic Redundancy Code
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
D8PSK	Differential 8-ary Phase Shift Keying
DCN	Data Core Network
DECT	Digital Enhanced (formerly "European") Cordless Telecommunications
DHCP	Dynamic Host Control Protocol
DLE	Data Link Entity
DLS	Data Link Services
DME	Distance Measuring Equipment
DMO	Direct Mode Operation
DQPSK	Differential Quaternary Phase Shift Keying
DSB-AM	Double Sideband Amplitude Modulation
DSSS	Direct Sequence Spread Spectrum
DULGARS	Dual Channel Ground and Airborne Radio System
DVSI	Digital Video Systems, Inc.
EDACS	Enhanced Digital Access Communications System
EDGE	Enhanced Data Rates for GSM Evolution
EIR	Equipment Identity Register
EMS	European Mobile Services
EPLRS	Enhanced Position Location Reporting System
ERF	Electronic Remote Fill

ESA	European Space Agency
E-TDMA	Enhanced Time Division Multiple Access
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Evolution
EV-DO	Evolution Data Only
EV-DV	Evolution Data & Voice
EVRC	Enhanced Variable-Rate Codec
FAA	Federal Aviation Administration
FAC	Forward Auxiliary Carrier
FANS	Future Air Navigation System
FCC	Federal Communications Commission
FCC	Forward Common Carrier
FCOCR	Final Communication Operating Concept and Requirements
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FED	Federal Government
FH	Frequency Hopping
FHSS	Frequency Hopping Spread Spectrum
FIS-B	Flight Information Service
Flash OFDM	Flash Orthogonal Frequency Division Multiplexing
FLIPCY	Flight Plan Consistency
FRC	Forward Reference Carrier
GACS	Global Aeronautical Communications System
GCNSS	Global Communication, Navigation, & Surveillance System
GEO	Geostationary or Geosynchronous Earth Orbit
GES	Ground Earth Station
GFSK	Gaussian Frequency Shift Keying
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Services
GSM	Global System for Mobile Communications
GSM-R	Global System for Mobile Communications Rail Extension
GTP	GPRS Tunneling Protocol
HAVCO	Have complied
HDLC	High Level Data Link Control
HFDL	High Frequency Data Link
HLR	Home Location Register
HR-DSSS	High Rate—Direct Sequence Spread Spectrum
IBSS	Independent BSS
ICAO	International Civil Aviation Organization
ICNIA	Integrated Communications Navigation and Identification Avionics
ICOCR	Initial Communication Operating Concept and Requirements
iDEN	Integrated Dispatch Enhanced Network
IDRP	Inter-Domain Routing Protocol
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineering
IETF	Internet Engineering Task Force
IFF	Identification Friend or Foe
IGSAGS	Integrated Global Surveillance and Guidance System

IMBE	Improved Multi-Band Excitation
IOTA	Isotropic Orthogonal Transform Algorithm
IP	Internet Protocol
IPsec	IP Security
IPT	Integrated Product Team
IPv4	IP version 4
IPv6	IP version 6
IRL	Implementation Readiness Level
ISDN	Integrated Services Digital Network
ISO	International Standards Organization
ITU	International Telecommunications Union
ITU-T	International Telecommunications Union—Telecommunications Sector
JRE	Joint Range Extension
JREAP	JRE Application Protocol
JTIDS	Joint Tactical Information Distribution System
JTRS	Joint Tactical Radio System
LAN	Local Area Network
LEO	Low Earth Orbit
LME	Link Management Entity
LoS	Line of Sight
LPI	Limited Probability of Intercept
LVT	Low Volume Terminals
MAC	Media Access Control
MAN	Metropolitan Area Network
MASPS	Minimum Aviation System Performance Standards
MC-CDMA	Multi-Carrier Code Division Multiple Access
MC-TDMA	Multi-Carrier Time Division Multiple Access
MDP	Mobile Data Peripheral
MDR	Multi-Mode Digital Radio
MEO	Middle Earth Orbit
MESA	Mobility for Emergency and Safety Applications
MHz	Megahertz
MIDS	Multifunctional Information Distribution System
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standards
MPDS	Mobile Packet Data Service
MRC	Mobile Radio
MRC	Mobile Router & Control
MSBN	Mobile Satellite Business Network
MSC	Mobile Switching Center
MSK	Minimum Shift Keying
MTSAT	Multifunctional Transport Satellite
NAS	National Airspace System
NASTD	National Association of State Telecommunications Directors
NATO	North Atlantic Treaty Organization
NCS	Network Control Station
NMS	Network Management System
NMS	Network Master Station
NOC	Network Operations Center
NPG	Network Participation Group

nrtPS	Non-Real-Time Polling Service
NSS	Network Subsystem
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
OTAR	Over The Air Re-keying
OTH	Over the Horizon
P2DP	Packed-2 Double Pulse
P2P	Peer-to-peer
P2SP	Packed-2 Single Pulse
P4SP	Packed-4 Single Pulse
PAMR	Public Access Mobile Radio
PAN	Personal Area Network
PCM	Pulse Code Modulation
PCN	Personal Communications Network
PCU	Packet Control Unit
PD	Packet (Mode) Data
PEI	Peripheral Equipment Interface
PMR	Private Mobile Radio
PoC	PTT Over Cellular
PPDR	Public Protection & Disaster Relief
PPP	Point to Point Protocol
PSPP	Public Safety Partnership Project
PSTN	Public Switched Telephone Network
PSWAC	Public Safety Wireless Advisory Committee
PTM	Point-to-Multipoint
PTP	Point-to-point
PTT	Push-To-Talk
QAM	Quadrature Amplitude Modulation
QCELP	Qualcomm's Code Excited Linear Prediction
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAC	Return Auxiliary Carrier
RCE	Radio Control Equipment
RFC	Radio Frequency Control
RFG	Radio Frequency Gateway
RFI	Request For Information
RFS	Radio Frequency Switch
RIU	Radio Interface Unit
RPDE	Rapid Preliminary Development Effort
RRC	Return Reference Carrier
RTCA	Radio Technical Commission For Aeronautics
RTP	Real-Time Transit Protocol
rtPS	Real-Time Polling Service
RTT	Radio Transmission Technology
RUDICS	Routed Unstructured Digital Interworking Connectivity Service
SA	Situation Awareness
SADL	Situation Awareness Data Link
SAIC	Single Antenna Interference Cancellation
SAM	Scalable Adaptive Modulation
SAP	Service Access Point

SARPS	Standards and Recommended Practices
SAS	Satellite Access Station
SATCOM	Satellite Communications
SC	Single Channel
SCADA	Supervisory Control and Data Acquisition
SCC	Satellite Control Center
SCDMA	See CDMA
SDLS	Satellite Data Link System
SDS	Short Data Service
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SINCGARS	Single Channel Ground and Airborne Radio System
SITA	Société Internationale Télécommunique Aéronautique
SMS	Short Messaging Service
SnAP	Subnetwork Access Protocol
SNMP	Simple Network Management Protocol
SOR	Statement of Requirements
STDP	Standard Double Pulse
TACP	Tactical Air Control Party
TARMAC	Taxi and Ramp Management and Control
TCP	Transmission Control Protocol
TCP/IP	Terminal Control Protocol/Internet Protocol
TDD	Time Division Duplex
TDL	Tactical Data Link
TDMA	Time Division Multiple Access
TD-SCDMA	Time Duplex-Synchronous Code Division Multiple Access
TEDS	TETRA Enhanced Data Service
TELCO	Telephone Company
TETRA	TErrestrial Trunked RAdio
TETRA MoU	TErrestrial Trunked RAdio Memorandum Of Understanding
TIA	Telecommunications Industry Association
TOC	Tactical Operations Center
TRL	Technology Readiness Level
TSR	Time Slot Reallocation
UAT	Universal Access Transceiver
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications Service/3G technology
UNNI	Unlicensed National Information Infrastructure
USSD	Unstructured Supplementary Service Data
UTRA	UMTS Terrestrial Radio Air Interface
V+D	Voice plus Data
VDL	Very High Frequency Digital Link
VHF	Very High Frequency
VLR	Visitor Location Register
VME	VDL Management Entity
VMF	Variable Message Format
VoIP	Voice over Internet Protocol
VSAT	Very Small Aperture Terminal

VSELP	Vector Sum Excited Linear Predictors
VSS	VDL Mode 4 Specific Services
WAN	Wide Area Network
WAP	Wireless Application Protocol
W-CDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WILCO	Will Comply
WiMAX	Worldwide Interoperability Microwave Access
WRC	World Radiocommunications Conference

APPENDIX G. ENDNOTES

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[1] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005.
[2] "An L-Band Digital Communications Link Concept for Air Traffic Control", MP 05B0000018, Dr. Warren Wilson, June 2005
[3] "L-Band Digital Link (LDL) Synchronization Performance", MP 05W0000345, Dr. Warren Wilson, January 2006
[4] "L-Band Digital Link for Air Traffic Services Data Communications", 2006 ICNS Conference Paper for Session B1 – Future Communication Study, Dr. Warren Wilson, 2 May 2006
[5] "E-TDMA Study Update", ICAO ACP WG-C-10 WP#10, Luc Deneufchatel, March 2006.
[6] "Development Program of Simulator for New Generation Aeronautical Satellite Communication System using IP in Japan", ICAO ACP WG-C-10 WP#9, Yasuto Sumiya and Akira Ishide, March 2006.
[7] "System Overview", MESA TR 70.012 v3.1.1, Project MESA Technical Specification Group – System, 2005-12, Section 4.1, page 8.
[8] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005
[9] Ibid, page 23.
[10] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005; additional references have been provided as applicable.
[11] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005.
[12] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005; additional references have been provided as applicable.
[13] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005.
[14] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005 and in Report ITU-R M.2014, Spectrum Efficient Digital Land Mobile Systems for Dispatch Traffic, 1998, p5; additional references have been provided as applicable.
[15] TIA Document, ANSI/TIA-902.BAAB-A, Wideband Air Interface Scalable Adaptive Modulation (SAM) Physical Layer Specification – Public Safety Wideband Data Standards Project – Digital Radio Technical Standards, September 23, 2003.
[16] TIA Document, TIA-902.BAAB, Wideband Air Interface Isotropic Orthogonal Transform Algorithm (IOTA) Physical Layer Specification Public Safety Wideband Data Standards Project – Digital Radio Technical Standards, March 2003.
[17] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005.
[18] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005; additional references have been provided as applicable.
[19] "The Global Link, CNS/ATM News for the Aviation Industry", April 2002, Issue Number 21
[20] Ibid.
[21] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005.
[22] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005; additional references have been provided as applicable.
[23] Source: See the Eurocontrol VDL Mode 2 Physical layer validation report, p. 37, Figure 1.22; From this figure, the MAXIMUM range was (uplink) above FL 350, and the value was taken from "RC trials"

[24] This assumes that the smallest guard time is between an uplink M-Burst and a downlink V/D Burst, or about 65 symbol periods between LBACS, minus the length of an uplink M-Burst (53 symbols) or about 12 symbols. At a rate of 10,500 symbols per second, this gives a maximum communications slant range of 185 nmi. See DO-224B for more details

[25] Assume same assumptions as used for VDL Mode 3 apply

[26] TLAT Appendix E; Segment E is the guard interval of duration of about 1250 microseconds (equivalent to about 205 nmi guard range), which includes segment D

[27] NASA CR-2005-213587 ITT Technology Assessment; The use of statistical self synchronization and a small guard band seems to indicate that the technology might become unstable at very large distances. Regardless, radio line of sight was used

[28] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.2.3, page 23.

[29] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005; additional references have been provided as applicable.

[30] Reference is ADL Technology Description in ACP WGC8/WP03

[31] "The Wireless Broadband (WiBro) System for Broadband Wireless Internet Services", Seug-Que Lee et al, IEEE Communications Magazine, July 2006.

[32] Ibid.

[33] Ibid.

[34] Maximum Range Supported is similar to VHF (200 nm at 30,000 feet, 80 nm at 5,000 feet); the UAT proposal is to establish a series of ground stations to provide coverage over the U.S. at low (5,000 feet) altitude; Assumed that the UAT maximum range is limited by LOS conditions.

[35] Estimated based on information in RTCA DO-282 Figure2-2 and Table 2-3 (estimated 3 dB bandwidth)

[36] Maximum Range Assuming LOS exists, range performance depends on traffic density and the 1090 MHz interference environment (i.e., ADS-B uses the same frequency as ATC transponder-based surveillance). In low density environments (e.g., oceanic) range performance is typically 100+ nm, while in a high-traffic density and 1090 interference environments (e.g., LAX terminal area) the range performance is on the order of 50 to 60 nm with current receiver techniques (improved processing techniques have been identified that are expected to provide range performance to 90 nm in dense nvironments)

[37] Estimated based on information in RTCADO-260 1090 Extended Squitter MOPS, Table 2-7

[38]Reference ICAO ACP Working paper, ACP WGC8/WP03, page 5

[39] Reference MP 05W0000345 "L-Band Digital Link Synchronization Performance", p. 16

[40] Physical layer for L-Band E-TDMA is not yet defined.

[41] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.2.3, page 23.

[42] A majority of the values specified in this table are based on information documented in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005; additional references have been provided as applicable.

[43] HAVEQUICK is a 7000 25kHz channel frequency hopped VHF technology

[44] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.2.3, page 23.

[45] Reference representative APC information provided at http://www.airfax.com/airfax/features/viewstory.asp?filepath=sep2005%5Caircell.htm

[46] [46] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.9, p190

[47] Note that AOC-only data loads were not considered as AOC-only traffic is not a focus of this study.

[48] Although the COCR specifies separate requirements for uplink traffic, downlink traffic, and combined, data rates considered for screening thresholds were only combined uplink and downlink traffic requirements (to provide more conservative consideration of required capacity)

[49] [49] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005

[50]Per "High-Level Feasibility Study of UMTS for Air Traffic Control", Eurocontrol.01, the system capacity is limited by the uplink data rate (see page 85, first paragraph of section 4.3). The data rate is asymetric and

the system capacity is limited by the uplink data rate. The maximum uplink data rate is 960 kbps. This limit occurs because the TDM 10 ms frames provide up to 9600 CDMA user data bits (max value assumming minimum CDMA spreading factor of 4). (100 frames times 9600 bits per frame gives the max uplink data rate of 960 kbps.) Assume CDMA spreading factor of 4 to maximize data capacity (and mobile antenna diversity and high-gain antennas are not necessarily available)

[51] "High-Level Feasibility Study of UMTS for Air Traffic Control", Eurocontrol, 8-31-2000, Eurocontrol.01 Although there are no explicit limitations, the study identifies cell size drivers including propagation environment, type of antennas used and antenna diversity. The study indicates that in the C-band environment, cell sizes from 10 - 100 km can be achieved (with the latter employing antenna diversity on mobile user and high-gain, sectorized antennas on the ground). For the VHF environment, the study calculates cell size ranges from 300 - 600 km (again with the latter accounting for antenna diversity on the mobile and high-gain ground antennas). Since the WCDMA concept of use may not employ mobile antenna diversity and high-gain ground antennas, we use the maximum derived range (300 km) without employing these techniques. 300 km = 162 nmi.

[52] NASA CR-2005-213587 ITT Technology Assessment, See Table 3.2-2 pg 22

[53] Ibid.

[54] CDMA2000 3x is comprised of multiple (3) CDMA2000 1xEV components. The maximum reverse link rate for CDMA2000 1xEV was multiplied by 3 to arrive at this data rate

[55] Assumed to be the same as CDMA2000 1xEVDO

[56] "1xEV: 1x EVolution, IS-856 TIA/EIA Standard, Airlink Overview", QUALCOMM, Inc, Nov 7, 2001, page 18 provides a table of modulation, code rates and associated data rates. The maximum 'reverse link' (MS to BS) is 153.6 kbps (range is 9.6 kbps through 153.6 kbps). The maximum 'forward link' is 2.5 Mbps (range is 38.4 kbps through 2.4576 Mbps)

[57] NASA CR-2005-213587 (Phase I FCS Technology Assessment) p. 29, Para. 3.2.4.2, "…CDMA2000 has a maximum cell size of 100 km. This limit is traceable to the design feature that uses a common spreading code from all ground stations with a phase offset large enough to unambiguously distinguish cell transmissions from that of its neighbors."

[58] Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Table 3.2-2 p 22

[59] Ibid, Table 3.2-2 p 22.

[60] [60] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, up to 2 Mbps peak data rate is supported by a single channel in a TD-SCDMA system p 36
Also see Table 3.2-2 pg 22

[61] Ibid, See Table 3.2-2 pg 22.

[62] Ibid.

[63] Ibid.

[64] Ibid, see Table 3.3-1 pg 41

[65] Ibid.

[66] Ibid.

[67] Ibid.

[68] This value is the minimum assuming 10 MHz channel, Tb or 22 2/9 microseconds and Tg = 1/4 of this (and QPSK modulation); See concept of use in "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005 for additional detail.

[69] Calculated from link budget shown on p. 33 of "Mobile WiMAX - Part 1: A Technical Overview and Performance Evaluation". Note that the link budget provides an allowable (free space) path loss of 128, which corresponds to 12.9 nm for a frequency of 2.5 GHz. or 6.28 nm at 5.150 GHz without range extension methods (mesh hops or higher power tx's); However, the link budget included 10 dB for "penetration" loss. This is because the WiMAX concept accomodates subscriber equipment inside of houses. This "wall penetration" factor was not deemed applicable for airport surface applications. Hence, a total loss of 138 dB was used, which corresponds to 19.9 nm at 5150 MHz.

[70] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005

[71] Ibid, but noting that basic range can be extended by multiple hops; assumed 3 hops = 3*8.1 = 24
[72] From TSB-102A: Data transmission over the RF link shall be allowed by the
system at a minimum gross bit rate of 9600 BPS with minimal re-transmissions. The net bit rate that is available after deduction of overhead for error correction and re-transmission is 5.8 kbps. Because of the concept of use (direct mode conventional system, with voice and data shared on the same channel) the system will not provide much data capacity. pp81
[73] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.4-2 p 56 (APCO P25 Phase 1 data)
[74] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.2.3, page 79
[75] ETSI EN 300 392-2 V2.4.2 (2004-02); Terrestrial Trunked Radio (TETRA); Voice plus Data (V+D); Part 2: Air Interface (AI): 4.7 Modulation - The modulation scheme is Pi/4-shifted Differential Quaternary Phase Shift Keying (Pi/4-DQPSK) with root-raised cosine modulation filter and a roll-off factor of 0,35. The modulation rate is 36 kbit/s. Figure 12 Types of Bursts shows 80 bits overhead for each 432 bits data
[76] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.4-2 p. 56
[77] Report ITU-R M.2014, Spectrum Efficient Digital Land Mobile Systems for Dispatch Traffic, 1998, p5.
[78] Ibid.
[79] Ibid, p.6.
[80] Ibid.
[81] Ibid, Note that this report uses the acronym "DIMRS" for iDEN, which is the common international reference
[82] Ibid.
[83] Ibid.
[84] Ibid, note that EDACS is FDM, and the comm. range is design dependent. We assume the technology is power limited, and assign it a max range commensureate with LOS at FL 180
[85] TIA-902.BBAB, Wideband Air Interface, Isotropic Orthogonal Transform Algorithm (IOTA) Physical Layer Specification: The P34 air interface varies between 81.4 and 799.2 kbps for the optional air interface (IOTA). The data rate provided depends on modulation complexity and channel bandwidth. The rate shown is for the 100 kHz channel with a 2ASK modulation type (this is the lowest possible modulation complexity). The 150 kHz channel with 2ASK modulation provides higher data rate (266.4); however this is not needed. Additionally, it was felt that the 8ASK, while providing a much higher data rate, would not be appropriate for an area communications system (insufficient range). Meanwhile the 2ASK meets the COCR sector requirements and likely closes the link in the specified distance
[86] Total guard time includes ramp down plus additional allocated guard time. Per IOTA TIA-902.BBAB, Figure 19 "Detailed view of random access slot", the ramp-down plus guard time is equal to 1 ms. This is equivalent to range of 162 nm.
[87] TETRA ENHANCED DATA SERVICE (TEDS), Dr. M. Nouri, Chairman of EPT Working Group 4 (WG4), Slide 18
[88] Ibid.
[89] An Overview of TETRA, Doug Gray, Chairman ETSI Project TETRA, Slide 13. TEDS is very similar to APCO P34 and has multiple defined channel widths (25, 50, 100 and 150 kHz) as well as multiple modulation schemes. The TEDS range is 36 to 691 kbps. The rate used here is for 150 kHz channel and 64 QAM.
[90] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.4-2 p. 56
[91] Note that SDLS and Custom Satellite System have been combined; Custom Satellite System is a more generic representation of SDLS. As requirements for SDLS are still under developed, it is envisioned that they would accommodate derived requirements for a future aeronautical communication system as would those of a custom satellite system. These items are essentially the same, albeit one is a more general representation of the other.
[92] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.5-2 p. 87; SDLS requirements indicate

that spot beam provides between 6.4 and 30 kbps in spot beams; For a general custom satellite solution, this values is responsive to maximum required value (per-user) of 28.6

[93] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.2.3, page 104

[94] Ibid, pg 111.

[95] "SwiftBroadband Capabilities to Support Aeronautical Safety Services, WP1: Technical Description and Application to ATS", TRS064/04, EUROCONTROL, Nov 16, 2005.

[96] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.5

[97] Ibid.

[98] Ibid.

[99] Ibid.

[100] Reference "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005. Fixed at 31.5 kbps raw channel burst data rate but with CSMA MAC, throughput is less than 20 kbps. (pp143); Note that the channel access mechanism (CSMA) reduces effective information throughput to less than 10 kbps. 10 kbps is used repeatedly in industry glossies on this technology and was used here; however, theory would indicate that the actual throughput will be somewhat less, perhaps as low as 28% of 31.5 kbps, or 8.82 kbps.

[101] See the Eurocontrol VDL Mode 2 Physical layer validation report, p. 37, Figure 1.22.;From this figure, the MAXIMUM range was (uplink) above FL 350, and the value was taken from "RC trials"

[102] RTCA DO-224B, p.147. Mode 3T has up to 3 bursts per Frame (120 ms) that can be used for user data. Each burst provides 192 symbols for user data. Each symbol is 3 bits. Note that this is NOT the information throughput, as channel coding is included in the above calculation, i.e. the 14.4 is a raw channel data rate and the info throughput is less (by the coding overhead)

[103] Here we have assmed that the smallest guard time is between an uplink M-Burst and a downlink V/D Burst, or about 65 symbol periods between LBACS, minus the length of an uplink M-Burst (53 symbols) or about 12 symbols. At a rate of 10,500 symbols per second, this gives a maximum communications slant range of 185 nmi. See DO-224B for more details. Page 155 is a good starting point, but is by no means sufficient to glean this detail

[104] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, p123.

[105] Assumed that the same assumptions as for VDL Mode 3 apply

[106] Technical Verification and Validation of TIS-B using VDL Mode 4 (SCAA_NUP_WP34_TVV_TIS-B_0.3) and TLAT Appendix E; the maximum number of time slots per transmission is 75
each time slot has 192 bits for user data

[107] TLAT Appendix E: Segment E is the guard interval of duration of about 1250 microseconds (equivalent to about 205 nmi guard range), which includes segment D

[108] No information was provided for data rate so VDL Mode 3 max throughput rate is assumed since PHYS layer proposed to use D8PSK

[109] The use of statistical self synchronization and a small guard band seems to indicate that the technology might become unstable at very large distances. Regardless, radio line of sight was used here

[110] Reference NASA CR-2005-213587 ITT Technology Assessment: ADL provides many Mbps in available bandwidth. pp162 (See Table 3.7-2 pp153); Source: ADL Technology Description.doc
Supported data rates per user: 128 kbps to 2 Mbps. Transmissions bit rates higher than 128 kbit/s are achieved by using more than one user group for the transmission of the bits of one user.

[111] ADL Technology Description in ACP WGC8/WP03

[112] "The Wireless Broadband (WiBro) System for Broadband Wireless Internet Services", Seung-Que Lee et al, IEEE Communications Magazine, July 2006.

[113] Ibid.

[114]Reference NASA CR-2005-213587 ITT Technology Assessment: See UAT data frame structure (Figure 3.7-1) on page 155. The ground station is allocated one 464 byte frame per second, which is much higer than any of the aircraft allocations. This value is used to derive provided data throughput.

[115] Reference UAT Technology Description.doc: Maximum Range Supported: Similar to VHF: 200 nm at 30,000 feet, 80 nm at 5,000 feet. The UAT proposal is to establish a series of ground stations to provide

coverage over the U.S. at low (5,000 feet) altitude. We assume that the UAT maximum range is limited by LOS

[116] Reference Mode-S Technology Description.doc: Used the data per squitter (112 bits) divided by the max squitter rate (once per second). See, for example, Figure 3.7-3 on page 157 of the NASA CR.

[117] Reference Mode-S Technology Description.doc: Maximum Range Assuming LOS exists, range performance depends on traffic density and the 1090 MHz interference environment (i.e., ADS-B uses the same frequency as ATC transponder-based surveillance). In low density environments (e.g., oceanic) range performance is typically 100+ nm, while in a high-traffic density and 1090 interference environments (e.g., LAX terminal area) the range performance is on the order of 50 to 60 nm with current receiver techniques (improved processing techniques have been identified that are expected to provide range performance to 90 nm in dense nvironments).

[118] WGC10-WP02-BVHF-Appendix page indicates a maximum of 280.8 ksymbols/second as a theoretical maximum signal rate. Using 64 QAM as the modulation type, this equates to a maximum bit rate of 1263.6 kbps (64 QAM and rate 3/4 coding). This is noted on page 19 of the briefing. However, we can't expect to close the link with this type of modulation. As a conservative measure, and as was done for all of the other adaptive modulation technologies, the lowest complexity modulation scheme and lowest coding rate was chosen. Hence, the data rate given is for QPSK, 280.8 kSps, and rate 3/4 coding (there is a rate =1 coding defined, but it doesn't seem likely that we can get by with no coding)

[119] Reference: ICAO ACP Working paper, ACP WGC8/WP03, page 5

[120] The specifics of the air interface are under development. Initial suggestions of 62.5 kbps are flexible. 100 kbps was selected to ensure a level playing field with other "on the drawing board" technologies.

[121] "L-Band Digital Link Synchronization Performance", MP 05W0000345, Dr. Warren Wilson, January 2006, p. 16

[122] Assummed data rate (technology is being specified as an FRS candidate in L-Band; It seems likely that it will provide data rates on the order of 100 kbps);

[123] Communication range value is assumed; it is evisioned that a custom broadband solution would be engineered with a long communication range

[124] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.8-12

[125] Communication range is amplifier depended (100-300 statue miles)

[126] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.8-12

[127] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, See Table 3.8-3 Maximum Range Supported: 40 Km, dependent on specific radio and amplifier p. 176

[128] Ibid, Table 3.8-10.

[129] [129] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Max range depending on amplifier (up to 300 miles).

[130] "Future Communication Infrastructure: Development of Technology Shortlist for Further Investigations", ICAO ACP WG-C20, Working Paper 13, Luch Deneufchatel, Klauspeter Hauf, Larry Johnsson, John MacBride, Eleuterio Esteban, Jacky Pouzet, March 2006.

[131] "Global Communication, Navigation & Surveillance System (GCNSS) System Architecture Description Document (SADD) Volume III – Space-Based Communication Navigation & Surveillance Enhancement", D794-10025-1 Vol. III, GCNSS System Architcture Development Team/The Boeing Company, 2004.

[132] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Section 3.5.3.2.

[133] [133] "Technology Assessment for the Future Aeronautical Communication System", NASA/CR – 2005-213587, TR04055, ITT Industries – AES, May 2005, Sections 2.2.4 through 2.2.11

[134] "Spectrum Considerations for Public Safety in the United States", Tewfik L. Doumi, IEEE Communications Magazine, January 2006.

[135] Matthias Pätzold, Mobile Fading Channels, (West Sussex, England: Wiley, 2002) p. 270

[136] "Digial Communications, Third Edition", John G. Proakis, McGRaw-Hill Inc., 1995.

[137] Proakis, p.298

[138] Ibid.

[139] From ICAO paper "Interference Susceptibilities of Systems Operating in the 960-1215 MHz Band Application to the Compatibility Analysis of the Future Communication System", ACP-WGF14/WP12.
[140] "MOPS for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B), Volume 1", by RTCA DO-260.
[141] David W. Matolak, Ph.D., Wireless Channel Characterization in the 5 GHz Microwave Landing System Extension Band for Airport Surface Areas (Ohio University, March 2006)
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[143] http://www.intel.com/network/connectivity/products/wireless/307327.pdf, p. 2
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[147] Dr. Robert M. Ward Jr., "Simulated Results of Proposed OFDM Structure in Multipath", IEEE 802.16.3c-01/48, March 2001
[148] V. Erceg et al., "Channel Models for Fixed Wireless Applications," IEEE 802.16 Broadband Wireless Access Working Group, IEEE 802.16a-03/01, June 2003
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13. ABSTRACT ***(Maximum 200 words)***
This report describes the process, findings, and recommendations of the second of three phases of the Future Communications Study (FCS) technology investigation conducted by NASA Glenn Research Center and ITT Advanced Engineering & Sciences Division for the Federal Aviation Administration (FAA). The FCS is a collaborative research effort between the FAA and Eurocontrol to address frequency congestion and spectrum depletion for safety critical air-ground communications. The goal of the technology investigation is to identify technologies that can support the long-term aeronautical mobile communication operating concept. A derived set of evaluation criteria traceable to the operating concept document is presented. An adaptation of the analytical hierarchy process is described and recommended for selecting candidates for detailed evaluation. Evaluations of a subset of technologies brought forward from the prescreening process are provided. Five of those are identified as candidates with the highest potential for continental airspace solutions in L-band (P-34, W-CDMA, LDL, B-VHF, and E-TDMA). Additional technologies are identified as best performers in the unique environments of remote/oceanic airspace in the satellite bands (Inmarsat SBB and a custom satellite solution) and the airport flight domain in C-band (802.16e). Details of the evaluation criteria, channel models, and the technology evaluations are provided in appendixes.

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